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Review

A Review on Solar Drying Devices: Heat Transfer, Air Movement and Type of Chambers

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Abstract: Food waste is one of the biggest challenges we are facing nowadays. According to the Food and Agriculture Organization (FAO) of the United Nations, approximately one-third of all food produced in the world is lost at some stage between production and consumption, totaling 930 million tons of food per year. Meanwhile, 10.5% of humanity suffers from malnutrition, 26% are overweight and greenhouse gases derived from the food industry account for between 25 and 30% of total emissions (8 to 10% referring to food waste), exacerbating the current climate crisis. To address these concerns, there has been a growing inclination to seek alternatives to fossil fuels, including the adoption of solar energy across diverse sectors, including the food industry. Actions are needed in order to change these patterns. This review article aims to provide an overview of recent developments in the field of solar food dehydration and the types of dehydrators that have emerged. Extensive research and bibliographic analysis, including other review articles, have revealed a growing focus on investment in this area to develop solar dehydrators that are increasingly effective but as sustainable as possible.

Keywords: solar energy; types of dryers; dryers designs; food application

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1. Introduction

As is generally known, fossil fuels take millions of years to form. The world's heavy reliance on non-renewable energy sources in its energy matrix leads to a depletion of reserves as consumption surpasses production [1]. The most alarming aspect of this reality is the environmental impact it carries, manifesting in numerous problems such as global warming (caused by excessive CO_2 emissions), acid rain (resulting from pollutants reacting with water vapor), air pollution and water contamination [2]. Consequently, the availability of fossil fuels is under threat, putting global energy production at risk [3]. Various agreements have already been established, such as the Kyoto Protocol and the Paris Agreement. The quest for alternative energy sources to replace fossil fuels is essential for environmental preservation and combating climate change [4].

The energy transition cannot be solved with the simple and sudden abandonment of fossil fuel sources. This process should provide for a gradual elimination to ensure stability, resilience and efficiency. The targets are well-defined: by 2030, global emissions related to the energy sector must reduce by 30% below 2019 levels and by 75% by 2040 to achieve the goal of zero net emissions by 2050 (United Nations Sustainable Development Goals). Although renewable energies are presented as alternatives, they currently do not produce enough energy to fully replace traditional sources.

Among renewable energy options, solar energy stands out as the most abundant. The sunlight that reaches Earth every day dwarfs all other energy sources on the planet, with a rate approximately 10,000 times greater than humanity's current energy consumption [5].

This vast potential of solar energy could theoretically meet all of mankind's energy needs if it can be harnessed and stored in a cost-effective manner.

When solar radiation passes through the atmosphere, some of it is absorbed or scattered due to clouds, air molecules, aerosols and water vapor. As a result, the direct normal irradiance (DNI) represents the solar radiation that directly reaches the Earth's surface (Figure 1).

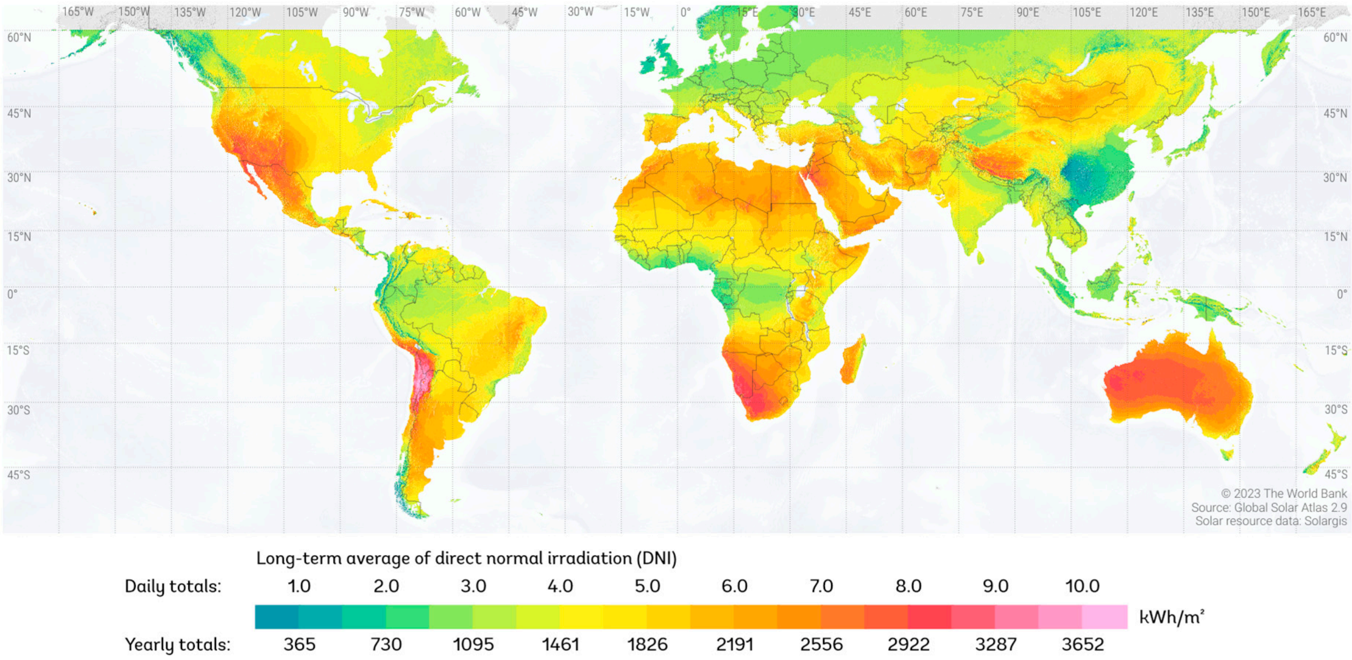


Figure 1. Solar resource map of direct normal irradiation (https://globalsolaratlas.info/map, accessed on 15 July 2023).

The solar constant, approximately 1367 W/m^2 at the mean Earth-Sun distance at the top of the atmosphere, represents the value of solar radiation [6]. Around 165 petawatts (PW) of solar energy are received on the Earth's surface. Out of this, about 30% is reflected back into space, while 47% is converted into low-temperature heat through various processes such as water evaporation (23%), wind (23%) and kinetic energy in waves (0.5%) [7]. On a clear day, at noon, the direct beam radiation on the Earth's surface can reach approximately 1000 W/m^2. The harvesting of solar energy is influenced by factors such as location, season, time of day and weather conditions [8]. Solar technologies offer a versatile range of applications, delivering heat, cooling, natural lighting, electricity and fuels, making them a vibrant research topic that attracts scientists to explore diverse approaches [9,10]. Solar energy is becoming increasingly popular due to its abundance, availability, cost-effectiveness and environmentally friendly nature. It is essentially free of charge, harnessing the sun's energy as a renewable and sustainable resource.

Regardless, the utilization of solar energy to dry fresh food products is one of the oldest preservation techniques used by humans. The earliest recorded instance of drying is for vegetables, dating back to the 18th century, by Van Arsdel and Copley (1963). Drying involves two fundamental and simultaneous processes: the transfer of heat to evaporate the liquid and the transfer of mass as a liquid or vapor within the solid and as a vapor from the surface. During the drying process, moisture transfer occurs in two main stages: external mass transfer, which involves the evaporation of moisture from the product's surface into the surrounding air and internal mass transfer, which refers to the movement of moisture from inside the product towards its surface [11].

The conventional drying system, known as open sun drying, involves directly exposing food to the wind and sun, spreading it in a thin layer over the ground or using trays. This method is commonly used for agricultural goods and other products, serving the purpose of preserving them for later use, especially in the case of food, or as an integral part of the production process, as seen in wood and tobacco drying. However, it comes with several limitations and challenges. One of the major drawbacks of open sun drying is the susceptibility of the crops to various external factors. This includes damage caused by birds, rodents, dust, rain, direct exposure to radiation, insect infestations and microorganisms [12–14]. Such issues can lead to significant post-harvest losses and negatively impact the overall quality of the dried products. Moreover, open sun drying requires a large area for the process to be efficient and it lacks the ability to control external drying parameters such as moisture content and temperature [15]. This lack of control can further contribute to inconsistent drying results and may not be suitable for certain products that require specific drying conditions. Given these disadvantages, there is a need for more advanced and controlled drying methods to minimize post-harvest losses and ensure better preservation and quality of dried food and other products.

The advancement in sun drying techniques has led to the development of solar drying systems composed of closed devices that trap and utilize the sun's radiation to increase the internal temperature [16]. The key difference between solar and solar drying lies in the utilization of equipment to collect the sun's radiation and trap it. Solar drying has found widespread application not only in agriculture but also in various industrial sectors, including the seafood, pharmaceutical, paper, ceramic and biomass processing industries [11]. Numerous studies have been conducted over time to investigate the dehydration of different types of crops using both open sun drying and solar drying devices, either as additional means or for comparison purposes [17,18].

The primary advantages of solar dryers over traditional sun drying are focused on drying times, higher efficiency, improved hygiene, healthier end products and cost-effectiveness [12]. By utilizing solar energy, these systems offer a more controlled environment for the drying process, leading to better quality and reduced post-harvest losses.

2. Technology of the Dryer

Solar dryers work based on the principle of transmitting heat from a source to the product being dried and facilitating the transfer of moisture from the product's surface to the surrounding atmosphere [19]. Successful food drying requires the removal of moisture from the product, with dry air absorbing it and air movement helping to carry it away [7]. Due to the aim of utilizing free and renewable solar energy, various types of solar dryers have been presented in the literature [20–27].

Researchers have explored different approaches to enhance the efficiency of these devices, such as improving insulation, heat recovery, recirculation and optimizing operating systems. Furthermore, achieving similar results can be possible by substituting the system's energy supply with combined heat and power methods [28]. Conventionally, solar dryers are classified in different ways according to heat transfer, air movement and type of chamber (Figure 2).

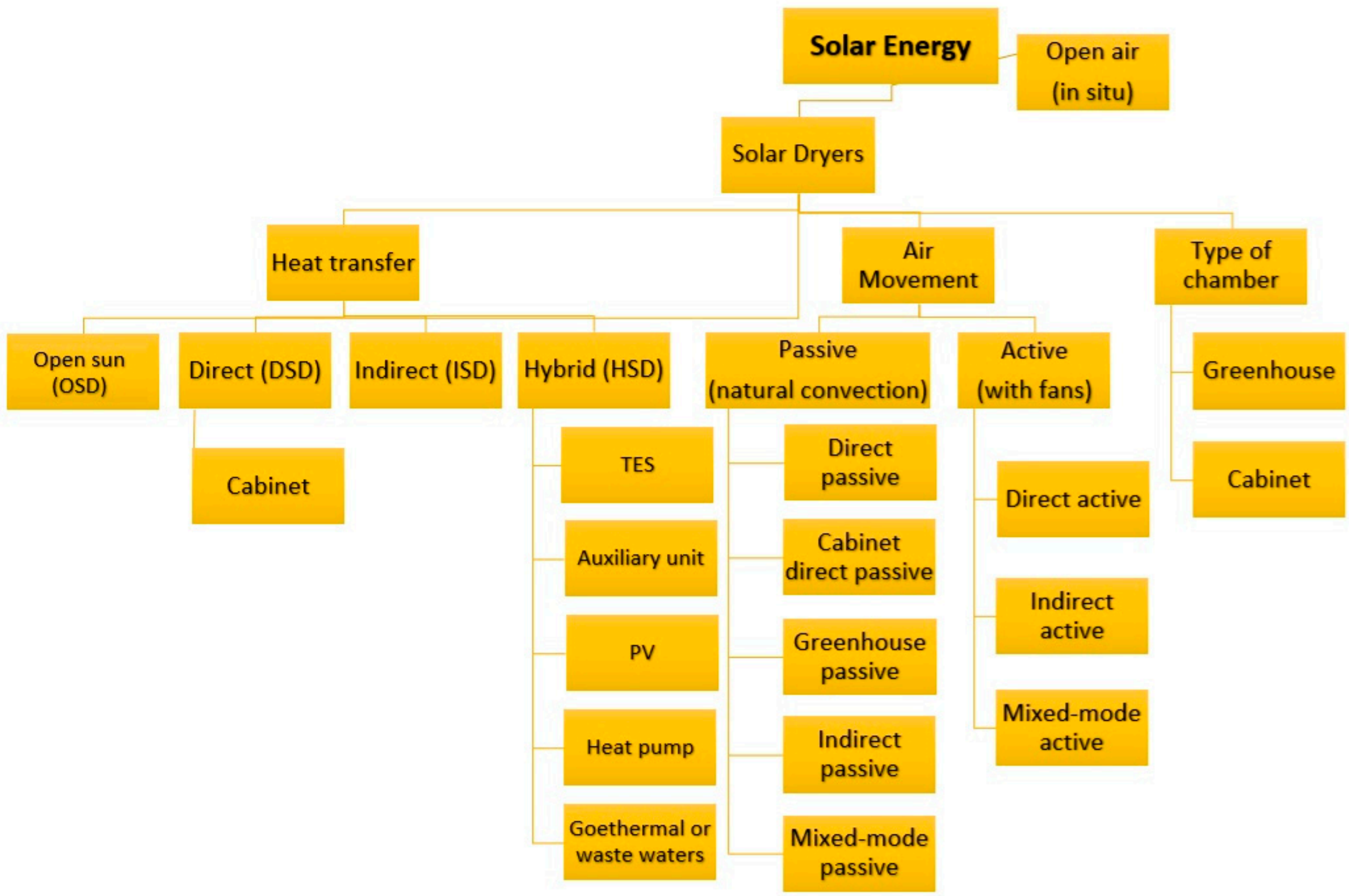


Figure 2. Schematic summary of the classification of solar dryers.

3. Working Principle

3.1. Mode of Heat Transfer

According to the incidence of the solar radiance as a working principle, the solar dryers can be classified into open sun, direct (with cabinet), indirect or hybrid [29]:

3.1.1. Open Sun Drying (OSD)

Also called natural drying, in this method, solar radiation directly impacts the surface of the crop, which is generally spread on the ground (Figure 3).

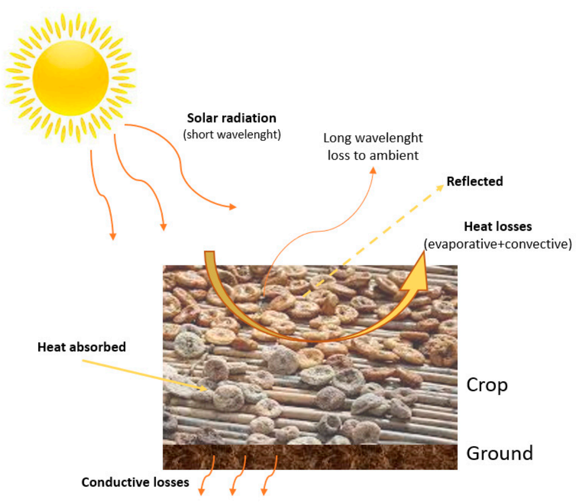


Figure 3. Schematic of working principle of open sun drying method.

Short-wavelength solar energy was received for the majority of the day, along with natural air circulation facilitated by the wind. The absorbed radiation converted into thermal energy increases crop temperature, which is improved by the color of the product, facilitating dehydration. There are some energy losses from reflective, evaporative and convective modes, which decrease the efficiency of the process (Table 1).

Table 1. Published studies related to OSD experiments.

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
Lab model vacuum-assisted solar dryer	The final moisture content of 11.5 ± 0.5% was 360, 480 and 600 min in a vacuum-assisted solar dryer and 450, 600 and 750 min in an OSD. The temperature inside the vacuum chamber was 48 °C when the ambient temperature was 30 °C.	Tomato slices	Canada	2007	[16]
compared with OSD	The maximum temperature difference between hot air and ambient air is 35.4 °C and the maximum efficiency of the setup is calculated at 55%.	Various	India	2019	[17]
Comparison of OSD and solar drying based on an evacuated tube collector	Reduction in drying time was 18.87% compared with the tilted system and 21.82% compared with the horizontal flat-plate system.	Banana	Thailand	2022	[30]
OSD with automatic dual-axis solar tracking	The instantaneous thermal efficiency of the solar collector varied between 30% and 80% at a mass flow rate of 0.047 kg/s. The overall energy efficiency of the solar dryer was 34%.	Red pepper	Tunisia	2019	[31]
Solar drying of red pepper with a mixed-mode solar greenhouse dryer (SGD) with forced convection compared with an OSD	The principal evaluation was in mycotoxins and the recommendation was to use a solar tent dryer to improve the safety of food during processing and preservation.	Plantain	Nigeria	2021	[32]
Experiment	The drying rate of solar dryers was higher than that of hot air dryers and OSDs. The aroma of dried mint was maintained in solar-dried samples but was lost in the hot air dryer and OSD.	Mint	India	2017	[33]
Solar tent, dried and OSD	From 79.8% to 20.2% of moisture content, it takes 120 h in indirect solar and 201 h in OSD.	Grapes	Morocco	2018	[34]
A comparative study of OSD, solar drying and hot air cabinet drying	Faster drying rate in active drying (18.67% in 9 h) compared to passive drying (24.24% in 12 h) and OSD (24.24% in 24 h)	Red Chilies	India	2020	[35]
Drying behavior of OSD and indirect solar dryers	Drying from 28% to 13% moisture content was 300 to 540 min; with black polythene and fertilizer bags, it was 120 to 156 min. Performance significantly varies with the drying pad and thickness of the paddy.	Paddy Rice	Sri Lanka	2021	[36]
A comparative study of solar hybrid greenhouse drying and OSD	Solar-tunnel (T1) and solar-cum gas (T2) are more efficient compared with OSD (T3). The T1 and T2 methods reduced the moisture level from 80% to 10–12% in 63 and 54 h, respectively, compared to the 81 h taken by T3.	Red Chilies	Pakistan	2022	[37]
OSD suitable drying conditions	The 10% vinegar as a pre-treatment showed no significant difference ($p \leq 0.05$) in the bacterial population reduction.	Ginger rhizomes	Ghana	2022	[38]
Comparison between Solar Tunnel, Solar-Cum Gas Dryer and OSD	The model was the best drying model with the highest correlation coefficient.	Figs	Turkey	2018	[39]

Strengths: independent of any source of energy; cheapest method; environmentally friend; Weaknesses: crops exposed to animals and weather changes; microorganism's contamination; discoloration by UV radiation; non-controlled drying.

3.1.2. Direct Solar Drying (DSD)

In direct solar drying, the sun is the only source of energy in all processes. The product can be exposed or protected, and solar radiation is incident on a transparent cover, typically made of plastic or glass (Figure 4).

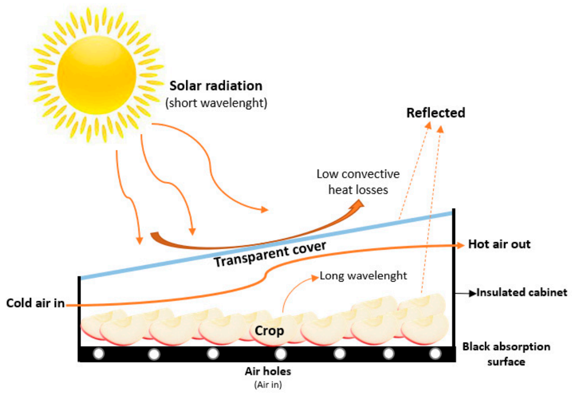


Figure 4. Schematic of working principle of direct drying method.

The glass reflects a portion of the solar radiation back into the atmosphere, while the remaining part goes into the drying chamber. Inside the chamber, some of the transmitted radiance is reflected back from the surface of the crop, while the rest is absorbed. This absorption leads to an increase in temperature inside the chamber and above the crop. The use of glass reduces convective losses to the environment. However, convective and evaporative losses still occur inside the chamber from the heated crop. The air entering the chamber through air holes and escaping through an aperture at the top of the cabinet takes the moisture away from the crop. Direct solar drying systems can be classified into various types, including cabinet-type, tunnel-type and greenhouse-type dryers, based on their specific configurations and designs. Each type offers distinct advantages and is suitable for different applications depending on factors such as the type of product being dried, local climate conditions and required drying efficiency (Table 2).

Table 2. Published studies related to DSD experiments.

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
Forced convention solar dryer	A black-painted solar dryer is 2–5 times more effective than an OSD.	Grapes	India	2021	[40]
Direct (cabinet type) operating at natural and forced convection and indirect (air heated by a solar water heating system)	Indirect solar drying has superior conditions, moderate drying times, better control of the operating conditions and greater protection against the effects of temperature compared with direct exposure to solar radiation.	Stevia leaves	Mexico	2018	[41]
Experimental studies on natural convection in open and closed solar drying using an external reflector	Compared to open solar drying, about 20% of energy could be saved by modified solar dryer with external reflectors	Anchovy fish	India	2022	[42]
Quality analysis and drying characteristics of turmeric (*Curcuma longa* L.) dried by hot air and direct solar dryers	Energy could be saved using the modified solar dryer with external reflectors.	Turmeric rhizomes	India	2021	[43]
Effect of film thickness and location of the sample inside a direct solar dryer on the drying kinetics of viscera silage in red tilapia	Higher effective diffusivity and lower drying time for DSD turmeric than HAD	Red Tilapia	Colombia	2020	[44]

Table 2. *Cont.*

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
Thin-layer DSD	The location of the sample inside the dryer and the film thickness affect the final product.	Mangoes	Burkina Faso	2011	[45]
Effect of direct solar drying on quality attributes of turmeric with computer vision technology	Drying rates and efficiency decreased with the number of drying days.	Turmeric rhizomes	India	2019	[46]
Single-slope DSD	Computer vision is a non-destructive technique that can be applied for online monitoring of quality control in the spice industry.	Red bananas	India	2021	[47]
DSD cabinet type	Forced convection is faster than natural; a novel kinetics model.	Tomatoes	Brazil	2021	[48]
Mathematical model for a DSD	Tomatoes 'Carmen' can be dried in 30 h.	Various	India	2022	[49]
DSD	Determination of optimal hole size and spacing between the glass and the absorber plate.	Various	USA	2006	[50]
DSD greenhouse type	Carotene content of solar-dried vegetables.	Pears	Portugal	2007	[51]

Strengths: protected crops; independent of any source of energy; cheap; environmentally friend; Weaknesses: limited to small scales; discoloration by UV radiation; moisture condensation inside transparent cover reduces transmittivity.

3.1.3. Indirect Solar Drying (ISD)

The principal differences between ISD and DSD are in their heat transfer and vapor removal methods. In indirect solar dryers, the crops are placed in trays or shelves inside an opaque drying cabinet in an independent unit from the solar collector (Figure 5).

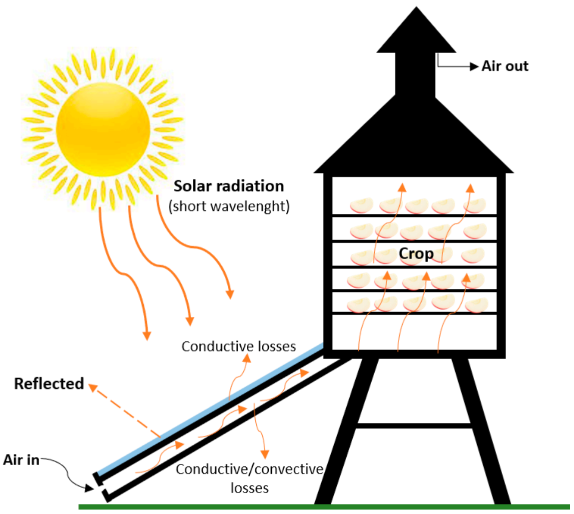


Figure 5. Schematic of working principle of indirect drying method.

The solar collector is responsible for heating the atmospheric air, which is then conducted to the drying chamber. The air can be heated actively using a fan or passively through natural convection. The heated air is then transferred to the wet crop, where it evaporates moisture. This occurs because of the difference in moisture concentration between the drying air and the surface of the material. The drying process in ISD happens as water is exchanged between the product and the flowing hot air (Table 3).

Table 3. Published studies related to ISD experiments.

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
Construction and study of a friendly solar ISD	A low-cost and environmentally friendly way to make home-made snacks with recycled materials	Various	Portugal	2022	[7]
A solar dryer with a flat plate absorber and thermal storage and natural convection	The economic performance of the dryer was analyzed based on the optimum cost of raw materials and the product sale price.	Leafy herbs	Jodhpur (India)	2015	[24]
Testing various solar dryers' designs	Laboratory models of direct (cabinet), indirect and mixed-mode solar dryers are designed and constructed to perform steady-state thermal tests for natural and forced air circulation.	n/a	Delhi (India)	2012	[26]
ISD: solar air heater with absorber systems in a flat-plate collector	The dryer was suitable for the preservation of mangoes and other fresh foods.	Mangoes	Malawi	2002	[52]
ISD with a single compartment	Thermal and economic performances of the designed dryer	Pears	Morocco	2022	[53]
Indirect forced cabinet solar drying + OSD	Effectiveness of IFCSD against the OSD	Apples	Kabul (Afghanistan)	2021	[54]
ISD	Development of an ISD and the performance and drying kinetics of brinjal and tomato	Tomato and brinjal	India	2021	[55]
Comparison between passive and active ISD	Forced convection performed better in all parameters than natural convection.	Carrots	Telangana (India)	2023	[56]
Natural convection ISD	The dryer was fabricated using low-cost, locally available materials with a simple design that can easily be replicated elsewhere in the world.	Apples	Japan	2016	[57]
ISD and OSD	Reduction from 10 to 4 days in the drying duration	Figs	Morocco	2018	[58]
ISD	The drying duration of the product was reduced considerably in comparison with traditional sun drying.	Bitter gourd	India	2008	[59]
ISD	Dryers built with low-cost materials, simple operation and high energy efficiency	Various	Mexico	2013	[60]
ISD with 2 collectors	Combining two types of collectors (natural and forced circulation) offers versatility in its operation.	Mangoes	Mexico	2017	[61]
ISD 2 collectors compared with OSD	The solar dryer accelerated drying more than two times over open-air sun drying.	Onions	China	2014	[62]

Strengths: better control over drying process; avoids direct exposition to sun, preserving quality; allows a lot of designs depending on the goal; Weaknesses: more expensive; requires higher temperatures; low drying rate, especially passive mode.

3.1.4. Hybrid Solar Drying (HSD)

Hybrid dryers are devices that combine two or more drying techniques, utilizing both direct solar radiation and electrical energy or stored heat, along with ventilators to ensure proper air circulation. These dryers can operate in forced convection or passive modes, depending on the design and application. The primary purpose of developing hybrid dryers is to overcome the limitations of other types of solar dryers and improve overall drying efficiency (Figure 6).

This kind of dryer can use various heating processes, such as fossil fuel, gas, biomass, or electric heating, in conjunction with solar heating. They often incorporate photovoltaic (PV) panels to generate electricity, which can be integrated into the drying system. For example, PV modules can capture solar radiation and convert it into electricity, which can power fans for forced air circulation integrated with greenhouse dryers. It is suitable for single and combined techniques, as well as direct and indirect types.

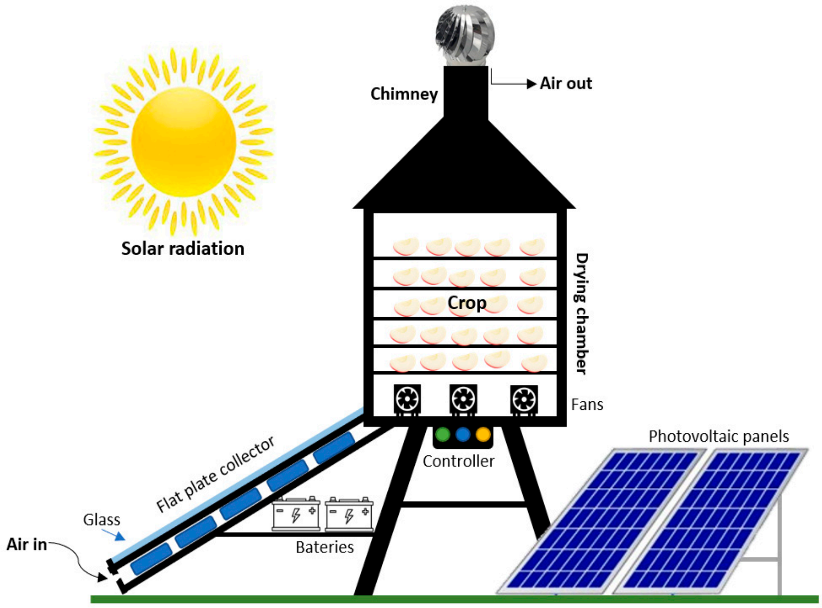


Figure 6. Schematic of working principle of hybrid (solar–thermal) drying method.

The principal components of hybrid dryers include a drying chamber made of materials such as aluminum or wood, a solar collector (e.g., a flat plate or other collectors) to capture and convert solar radiation into thermal energy and an additional energy generator or accumulator for heat exchange. In cases where solar energy is utilized, the PV module captures solar radiation and converts it into electricity, while the collectors absorb solar energy to increase the air temperature. The heated air is then directed into the drying chamber to reduce the moisture content of the crop. Fans ensure forced air circulation and are powered by the electricity generated from the PV module.

By combining different energy sources and techniques, hybrid dryers offer more control over the drying process, allowing for better optimization of drying conditions and improved product quality (Table 4).

Table 4. Published studies related to HSD experiments.

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
HSD, DSD and OSD comparison	The efficiency of agricultural dryers is increased through the use of a combination of solar and heating elements powered by a photovoltaic (PV) solar panel, compared to conventional dryers with only solar or biomass heating sources.	Tomato	Nigeria	2016	[63]
HSD heater powered by liquefied natural gas	Results suggest that the hybrid solar dryer is faster than both open sun drying and natural solar drying. HSD at 40 to 100 °C increases dryer efficiency (13 to 17%).	Sugar-palm vermicelli	Indonesia	2020	[64]
Indirect active hybrid solar-electrical dryer	The influence of drying air temperature on the variation of moisture versus drying time on the food process is more important compared to the influence of air-drying velocity.	Tomato	Algeria	2009	[65]
HSD with solar panels and electric resistances	Dryer efficiency proved useful for designing an industrial-level HSD.	Mushrooms	Chile	2013	[66]
HSD with liquefied petroleum gas	The dryer needs improvements because it is able to dry the lime, but the temperature may damage the fresh goods.	Lime	Java (Indonesia)	2020	[67]

Table 4. *Cont.*

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
ISD (improved solar dryer) and SPE (solar photovoltaic and electric) compared with OSD	Superior performance of the ISD and SPE dryers than the OSD method; reduced costs for ISD than SPE	Pineapple slices	Uganda (Africa)	2020	[68]
Indirect-type domestic HSD	Dryer construction and exergy analysis, drying kinetics and performance evaluation	Tomatoes	Delhi (India)	2022	[69]
PV/T unit, V-corrugated collector, heat storage unit and drying chamber	Three cases of no phase change material (PCM), PCM only and nano-enhanced PCM were used. PCM proved to be effective in terms of lowering the temperature inside the chamber. Recirculation of heat may be needed.	Mint	Iran	2022	[70]
Electric and solar hybrid solar ovens	Hybrid performance and thermal control maintain temperature stability, which allows cooking.	n/a	Argentina	2012	[71]
Hybrid thermal energy storage system	Solar energy is stored during sunny days and released later during cloudy days or at night. Electricity consumption is minimized.	n/a	Québec (Canada)	2006	[72]
PV/T greenhouse dryers compared with OSD and shade	The hybrid PV/T dryer proved to be more efficient in terms of moisture evaporation and heat transfer coefficient.	Grapes	New Delhi (India)	2008	[73]
Hybrid PV solar dryer compared with OSD	The dryer suits the purpose and prevents spoilage and post-harvest losses.	Tomatoes	Yola (Nigeria)	2017	[74]
Solar energy with biomass-fueled air heating	Dry fish in 15 h	Fish	Aceh (Indonesia)	2018	[75]
HSD	The total energy required is 89.9 kWh and the solar energy contribution is 66%.	Salted silver jewfish	Malaysia	2016	[76]
Solar-biomass HD	Pretreatments like microwave blanching followed by brine solution dipping of carrots prior to drying affect the quality of dried carrots positively.	Carrot slices	Bhopal (India)	2018	[77]
Indirect HSD	The indirect solar dryer performance was investigated with and without PCM, during the day and at night.	n/a	Tunisia	2017	[78]

Strengths: continuous drying even without sun and during the night; reduces drying time because it does not depend on the weather; Weaknesses: bigger environmental footprint; running costs.

3.2. Mode of Air Movement

Another way to classify the types of solar dryers is by taking into account the air movement. They are classified into passive, when they use natural convection; active, where the utilization of an electric fan creates airflow [79]; and mixed-mode, when both types are used.

3.2.1. Passive Solar Dryers Systems

Often referred to as natural ventilation or convection solar dryers, they depend on the normal movement of the air that is heated by solar energy and spreads on the crop's surface. In passive-mode dryers, there are several types available.

Direct Passive Solar Dryers

In a direct passive solar dryer, the crop is protected with a transparent cover, allowing solar radiation to pass through. It is then converted into thermal energy within the drying chamber through the greenhouse effect. The primary objective of this type of solar dryer is to reduce the moisture content of the products and this is achieved through the process of evaporation by diffusion [80,81].

Cabinet Passive Solar Dryers

The passive solar cabinet dryers [82] are generally inexpensive and straightforward to construct. They consist of a small box, most of the time made of wood, painted black to better absorb the solar radiation transmitted through a plastic or glass cover. Normally, the products to dry are placed in aluminum or plastic trays with wire mesh or perforated at the bottom. The trays are spaced apart to ensure adequate airflow through the products. The base of the cabinet is designed with holes to allow ambient air to enter, pass through the product placed on the wire mesh trays and then escape through holes at the top of the cabinet, carrying away moisture vapors [83].

Compared to open sun drying and direct passive solar dryers, this type of dryer has demonstrated better efficiency and improved product quality. The enclosed cabinet design and controlled airflow help create a more favorable drying environment, minimizing the negative effects of external factors such as dust, insects and weather changes. The black-painted surface of the cabinet facilitates better solar energy absorption, promoting more efficient drying.

Some authors classify cabinet solar dryers into normal and reverse absorber types [84]. The normal absorber represents the basic structure of a common passive solar cabinet dryer. The biggest disadvantages are the discoloration of the crop and the convective heat loss. In the reverse absorber cabinet, a reflector is placed under the drying chamber. The transparent cover is tilted at a 45° angle to maximize solar radiation exposure. The absorber plate captures the solar radiation and directs it to the reflector, which then redirects the solar heat to the drying chamber. As a result, the hot air enters the cabinet and circulates through the crop, effectively removing its moisture content with the heated air. The hot air becomes humid due to moisture evaporation from the crop and is eventually released through a vent or exit hole in the cabinet.

Greenhouse Passive Dryers

The utilization of a greenhouse dryer is a way to optimize direct solar drying. It is based on a structure with extensive glazing walls and roofs (glass, fiber-reinforced polymers and polyethylene film) and is divided into dome types, which are better for maximum utilization of global solar radiation and roof types, which are better for suitable mixing of air inside. They can also be called tent dryers; they are designed with vents of appropriate size and position to have controlled air flow. The air flow into the dryer can be controlled by rolling or unrolling the cladding at the bottom edge of the front side. The drying chamber is heated by the incident solar radiation and the heated air becomes less dense than the ambient air, which leads to the dehydration of products. The crop is laid on the floor above plastic sheets or in trays. The remotion of moisture occurs by natural convection [22,27,31,85–87].

Indirect Passive Solar Dryers

This is an indirect solar dryer that operates on the principle of natural convection. In the drying chamber, the crop is dried with the help of hot air provided by the solar air heater, and it passes out via an overhead vent. Crops are spread on trays without overlapping inside the drying chamber. The air flow rate is very low, as is the heat transfer [52,56,88–90].

Mixed-Mode Passive Solar Dryers

These dryers have the advantage of using both direct and indirect airflows. The passive mode of airflow depends on weather conditions combined with the greenhouse effect. Solar energy is captured directly in the drying chamber and indirectly through the solar air heater or collector. Such dryers can be used for a variety of crops that are suitable for low-temperature thermal drying (Figure 7) [21,91–95].

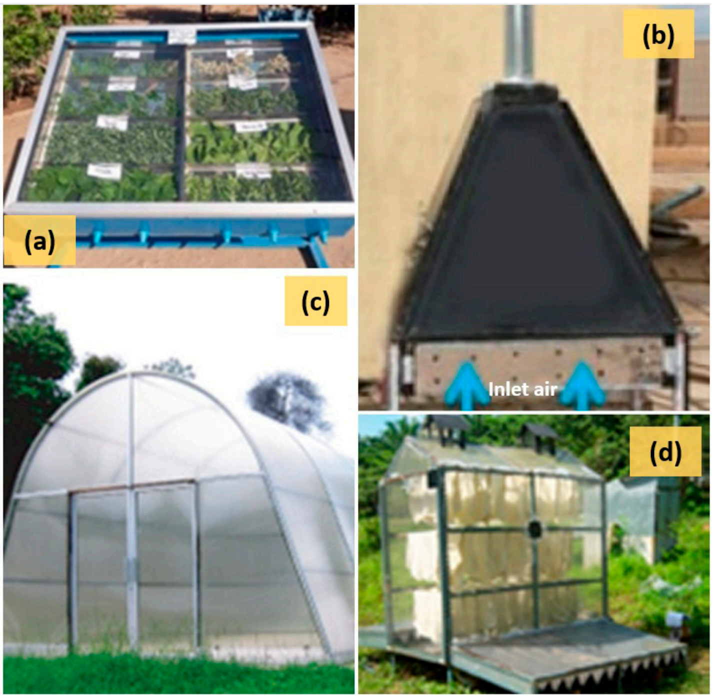


Figure 7. Examples of passive solar dryers: (**a**) direct [96]; (**b**) cabinet [97]; (**c**) greenhouse, dome type [98]; (**d**) mixed-mode [99].

3.2.2. Active Solar Dryers Systems

In the sequence of open sun drying and passive solar dryers, the active ones started to be built. They work on the principle of forced convection to transfer heat, using fans or ventilation. They can sometimes incorporate external heaters to preheat incoming air. These dryers are suitable for crops with high water content and do not require very high drying temperatures. There is a large variety of designs that can be divided in direct, indirect and mixed-mode dryers [100,101].

Direct Active Solar Dryers

The structure is almost the same as passive. The introduction of fans or blowers creates a forced draft in the dryer. They can be cabinet or greenhouse-type.

Indirect Active Solar Dryers

These kinds of devices have a separate collector and drying chamber. Due to the separate air heating unit, higher temperatures can easily be obtained with a controlled air flow rate. Products dried in this dryer are found to have good nutrient quality and color. Studies show that the influence of drying air temperature on the variation of moisture versus drying time in the food process is more significant compared to the influence of air-drying velocity [65,102,103].

Mixed-Mode Active Solar Dryers

Mixed-mode active solar dryers have almost the same design as passive ones, with the incorporation of fans or blowers. Both the solar collector and drying chamber receive solar radiation, which makes the mixed-mode dryer more efficient for the drying process due to its higher thermal rate (Figure 8; Table 5) [95,104].

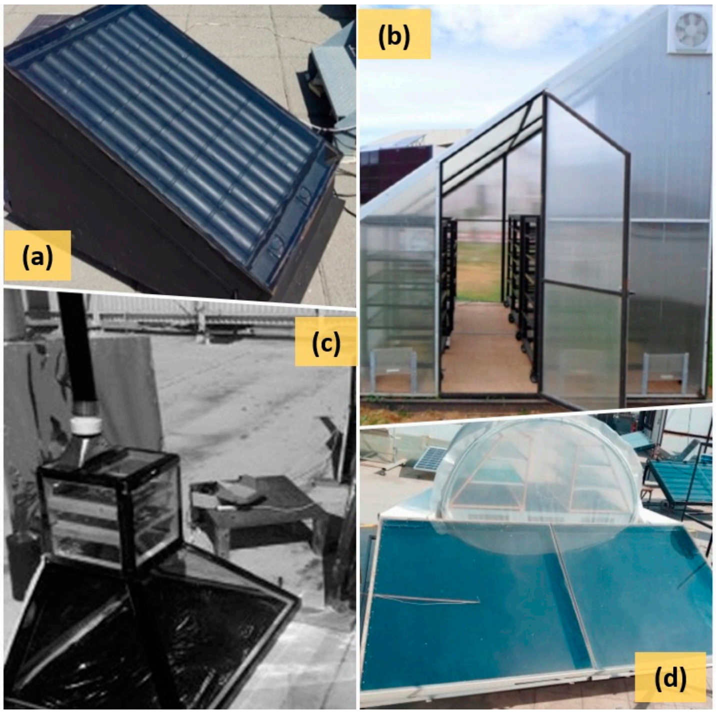


Figure 8. Examples of active solar dryers: (**a**) indirect [7]; (**b**) greenhouse, roof even- type [105], (**c**) direct with concentrating panels [106]; (**d**) mixed-mode tent-type [107].

Table 5. Published studies related to different devices according to the mode of air movement.

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
UV sheet cabinet-type solar dryer	Forced convection drying is the most efficient way of drying when compared to natural and open sun drying.	Banana	India	2022	[79]
NCD-FCD-HPD	The drying rate increases with the increase in temperature and speed of the drying air.	Mushrooms	Turkey	2021	[108]
Passive flat-plate collector solar dryer	Drying took 36.36% less time than OSD.	Mushrooms	India	2020	[109]
Shade drying, sun drying and solar drying	The more efficient method was conventional solar drying along with air recycling with a higher drying rate.	Pistachio nuts	Iran	2020	[110]
ISD- OSD	Changes in weather during the day affect the water activity of dried products.	Mint leaves	Afghanistan	2021	[111]
Compact solar cabinet dryer	For 47–50 °C, the dryer is suitable.	Pork meat	Thailand	2017	[112]
ISD	ISD outperforms OSD in efficiency and acceptability of products.	Amaranth leaves	Mozambique	2021	[113]
Solar greenhouse	The drying temperature of the tomato waste varies between 40 and 58 °C and takes 5 h.	Tomatoes	Algeria	2019	[105]
ISD	The study established a model of thin-layer drying of mango.	Mangoes	Burkina Faso	2009	[114]
Mixed-mode PV+ solar tunnel dryer	STD provides chips in good quality and suitable for rural areas	Potatoes	Saudi Arabia	2018	[115]
Mixed-mode and direct-mode solar dryers	Mixed modes A solar dryer can dehydrate vegetables to a moisture content of below 10%, transforming perishable vegetables into stable products.	African indigenous vegetable and chili	Kenya	2017	[104]

Table 5. *Cont.*

Principle of Study	Principal Achievements	Crop/Product	Location	Year	Ref.
Hybrid mixed-mode solar dryer	Suitable for a wide range of perishable agricultural products	Peaches, apples, chilli	Pakistan	2023	[116]
Mixed-mode solar dryer	Solar drying of injera is a feasible method for preserving and maintaining the quality of dried injera (dirkosh) with a minimum cost.	Injera	Ethiopia	2021	[117]
Mixed-mode and direct-type solar dryers	MMTD values are higher than DMTD except for water depletion.	Ginger	India	2022	[118]
Direct solar dryer with three axial flow fans	The drying system can be used for a wide range of agricultural products.	White Oyster Mushroom	Malaysia	2015	[119]
Mixed-mode natural convection dryer	Drying efficiency was evaluated at 12.3% when tested under the full designed load.	Cassava	Ghana	2007	[120]
ISD	The final moisture contents for thymus and mint were reached after 34 and 5 h.	Thymus plant/mint	Egypt	2013	[121]
Concentrating solar panels	Faster drying rates are achieved with solar concentrators.	Tomatoes	USA	2012	[106]

3.3. Type of chamber

Another way to divide the classification of solar dryers is based on the type of chamber, which can be a greenhouse or cabinet, as previously described. There are a variety of ways to dispose of the products to dry. They can be placed on trays or racks inside, or the chamber can be similar to a conventional oven, with various configurations. In the case of mixed-mode dryers, the chamber integrates both direct and indirect heating methods effectively. For hybrid dryers, the chamber is designed to accommodate both solar heating components and the additional energy source. The choice of chamber type is crucial to optimizing all the processes and achieving good drying results.

4. Hybrid Solar Dryers

This kind of dryer is, by definition, designed and constructed using direct solar energy and a heat exchanger. The products are dried under direct solar radiation and/or backup energy or stored heat when sunlight is not available. These types of dryers are used in single and mixed modes of drying. Several studies have been developed to test different techniques to improve solar dryers, considering the possible use of thermal storage materials, the deep bed drying method, improved solar collector designs and energy hybridization. They can be divided several ways, depending on their construction [107,122,123].

4.1. With Thermal Energy Storage (TES)

Due to the limitation of solar dryers operating only during sunlight hours, thermal storage emerges as a great solution. It allows the stored heat to be used during the night, ensuring continuous drying and preventing rehydration of the products. During off-sunshine hours, microbial activity may lead to the growth of microorganisms and the extended drying periods can degrade the quality of agricultural products, resulting in poor product quality and spoilage [66,124–132].

The integration of a TES unit is needed, and numerous studies have tested it. Some authors divided it into:

Sensible heat storage (SHS): materials are heated to store excess solar energy, depending on their specific heat capacity, mass and temperature. The best properties of these materials are density, thermal conductivity and stability. For example, materials such as brick, aluminum, gravel, river rocks, concrete, granite and limestone can be used. The rock bed is the most common material for sensible storage used in solar dryer systems [133,134];

Latent heat storage (LHS): in this kind of material, solar energy is stored during the phase change process. The phase change materials (PCM) can be organic (such as paraffin, like wax n-alkanes and methyl groups) or non-paraffin types (like fatty acids, glycols, alcohols and esters), inorganic (salt hydrates and metallic) or eutectic composition [128,135];

Thermo-chemical energy storage (TCES): it is based on the principle that all chemical reactions either absorb or release heat. This process stores energy by using high-energy chemical processes. In this case, the heat stored depends on the amount of storage material, the endothermic heat of the reaction and the extent of conversion [136–138].

4.2. With an Auxiliary Unit

The dryer can operate on solar energy, but for additional heating, auxiliary units are used. The most common are fuelled with fossil fuel or biomass to reach and maintain the required temperature. Despite their effectiveness, their availability is limited, and they are associated with environmental pollution issues. Amer and Gottschalk [139] used electric resistances as auxiliary units in fresh chamomile drying; Matouk et al. [140] used them for onion slices; and Hossain et al. [141] used them for tomato slices [142]. Ferreira et al. [143] applied 20 incandescent lamps, 100 W each, for drying banana slices. Suherman et al. [144] used SUS (stainless steel) plates as heat collectors for solar radiation and an LPG (liquefied petroleum gas) burner in seaweed drying. Many studies have been conducted on this type of dryer in various contexts [145].

4.3. With Photovoltaic (PV)

Solar dryers with PV assistance are probably the most widely used. Thermal energy can be obtained from solar radiation by using solar collectors and it is converted via PV panels into direct current electricity [146]. These kinds of systems have a huge variety of possible configurations and can range from the simplest forms, such as powering fans to provide air circulation, to making a significant contribution to the decarbonization of electricity production. The PV-ventilated system is very common in greenhouse dryers [147–152]. The integrated arrangement for applying thermal energy as well as electrical energy with a PV module is referred to as a hybrid PV/T system [18,73,153–161]. The integration of PV panels with solar dryers ensures a continuous and reliable power supply, reducing dependency on the grid and further promoting sustainability in the drying process.

4.4. With Heat Pump

Some authors defend that combining a solar thermal energy source, such as solar thermal collectors with a heat pump dryer, will assist in reducing the operation cost of drying and producing products of high quality [162]. The aim of installing a heat pump is to solve the problem of the intermittent availability of solar radiation. Depending on weather conditions, four working modes can be chosen [163–174]:

Solar energy heating mode, when solar radiation is sufficient during the daytime;
Heat pump heating mode when solar radiation is unavailable;
Solar-assisted heat pump heating mode, when solar radiation is insufficient during the daytime;
Heat pump dehumidification mode when ambient humidity is high.

Beyond all the drying designs associated with heat pump systems, some authors also consider solar systems with chemical heat pumps (CHP) and solar systems with dehumidification systems [13].

The chemical reactions in a CHP system are generally reversible, enabling the alteration of the temperature level of the thermal energy stored by chemical substances [175,176]. These reactions are crucial for absorbing and releasing heat. Typically, the main components include an evacuation system, a storage tank, a chemical heat pump and a drying chamber. CHP can be categorized into solid–gas [177] and liquid–gas.

A solid–gas chemical heat pump unit consists of a reactor or adsorber, an evaporator and a condenser. Liquid–gas systems have at least two reactors: endothermic and exothermic. The high storage capacity, low heat loss and long-term storage of reactants and products are the principal advantages of CHP [178].

Regarding dehumidification systems, in general, fresh products have high moisture contents. Using a desiccant material, such as silica, alumina, pillared clay, or zeolite [179–181], may consume low energy and produce dry air to improve drying performance. The pressure difference of generated water vapor, even at low temperatures, can improve driving force that is proportional to the evaporation rate. As a result, energy efficiency can be potentially improved while maintaining product quality [182].

Heat pump dryers come in different types and their performance varies depending on the type. The ability to control the temperature of the drying air and humidity while recovering energy from exhaust is one of the primary advantages of heat pump dryers; however, the environmental impacts is still not well known [183].

4.5. With Geothermal or Waste Waters

This kind of dryer uses solar radiation in combination with a low-potential energy source, such as geothermal or wastewater. The installation allows for the combination of conventional or nonconventional energy sources [184]. According to Ivanova and Andonov [185], it is possible to achieve continuous drying, even during the night, enabled by additional heating of the air during movement in the collector using this source of energy, in a clean and cost-effective mode, as renewable energies are used. The system includes a stainless-steel body, heat exchanger, piping, dehumidifier, blower and trays [186].

Based on the design, construction material used, energy backup systems and auxiliary heating units, several variants of solar dryers for drying foods have been described. These diverse configurations allow for customized solutions to suit specific drying requirements, optimizing energy efficiency and ensuring consistent drying performance across different applications. The integration of low-potential energy sources with solar radiation enhances the versatility and reliability of solar dryers, making them more sustainable and resilient in various operating conditions.

Several studies are being conducted to test different techniques for improving solar dryers, including the use of thermal storage materials, deep bed drying methods, enhanced solar collector designs and energy hybridization. As we can observe, there are a wide variety of solar dehydrators with different shapes and operating modes. The possibilities are so many that, in recent years, several authors have felt the need to write review articles on the subject (Table 6).

Table 6. Overview of published review articles using solar energy dryers, since 2010.

Title	Year	Ref.
Review of solar dryers for agricultural and marine products	2010	[187]
A Review of Photovoltaic Thermal (PVT) Technology for Residential Applications	2010	[157]
Solar dryer with thermal energy storage systems for drying agricultural food products: A review	2010	[131]
Solar drying	2011	[188]
The development of fruit-based functional foods targeting the health and wellness market_ a review	2011	[189]
New Technologies of Solar Drying Systems for Agricultural and Marine Products	2012	[190]
Solar drying of agricultural products: A review	2012	[191]
Performance study of different solar dryers: A review	2014	[9]
A Review of Solar Dryer Technologies	2014	[20]
Solar greenhouse drying: A review	2014	[85]
Osmotic dehydration of fruits and vegetables: a review	2014	[192]
Applications of software in solar drying systems: A review	2015	[19]
A review on indirect solar dryers	2015	[193]
Direct Type Natural Convection Solar Dryer: A review	2015	[81]
Performance enhancement of solar collectors—A review	2015	[194]
A Review on Solar Drying of Agricultural Produce	2016	[13]

Table 6. *Cont.*

Title	Year	Ref.
Development and recent trends in greenhouse dryer: A review	2016	[22]
Progress in solar dryers for drying various commodities	2016	[29]
Identifying the effective factors on implementing the solar dryers for Yazd province, Iran	2016	[195]
Solar fruit drying technologies for smallholder farmers in Uganda, a review of design constraints and solutions	2016	[196]
A review on solar tunnel greenhouse drying system	2016	[152]
Thermal energy storage based solar drying systems: A review	2016	[125]
Review on various modelling techniques for the solar dryers	2016	[88]
Review on methods for preservation and natural preservatives for extending the food longevity	2017	[197]
Solar dryers for tropical food preservation: Thermophysics of crops, systems and components	2017	[198]
An investigation on solar drying: A review with economic and environmental assessment	2018	[15]
Evaluation of food drying with air dehumidification system: A short review	2018	[180]
A comprehensive review on different kinds of solar dryers and their performance	2018	[199]
Decontamination of Microorganisms and Pesticides from Fresh Fruits and Vegetables: A Comprehensive Review from Common Household Processes to Modern Techniques	2019	[200]
Recent advances in sustainable drying of agricultural produce: A review	2019	[201]
Solar Energy on Demand: A Review on High Temperature Thermochemical Heat Storage Systems and Materials	2019	[137]
Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach	2020	[202]
A review on indirect type solar dryers for agricultural crops—Dryer setup, its performance, energy storage and important highlights	2020	[89]
A review of construction, material and performance in mixed mode passive solar dryers	2020	[95]
Solar assisted heat pump system for high quality drying applications: A critical review	2020	[162]
A review on recent innovations and developments in greenhouse solar dryers	2020	[203]
Advanced technologies and performance investigations of solar dryers: A review	2020	[204]
Analysis of recent developments in greenhouse dryer on various parameters- a review	2020	[205]
Solar dryers for food applications: Concepts, designs and recent advances	2020	[206]
Integration of solar heating systems for low-temperature heat demand in food processing industry—A review	2021	[10]
Recent advancements in technical design and thermal performance enhancement of solar greenhouse dryers	2021	[207]
Global advancement of solar drying technologies and its future prospects: A review	2021	[122]
Natural convection and direct type (NCDT) solar dryers: a review	2021	[80]
A review on solar dryers integrated with thermal energy storage units for drying agricultural and food products	2021	[128]
A review of the indirect solar dryer with sensible heat storage mediums	2021	[133]
Application of Geothermal Water for Food and Crop Drying	2021	[186]
Energy, exergy and techno-economic performance analyses of solar dryers for agro products: A comprehensive review	2021	[208]
Importance of integrated CFD and product quality modelling of solar dryers for fruits and vegetables: A review	2021	[209]
A review on the use of sorption materials in solar dryers	2021	[210]
A review on performance evaluation of solar dryer and its material for drying agricultural products	2021	[211]
Recent advancements of PCM based indirect type solar drying systems: A state of art	2021	[212]
Solar drying Technologies: A review and future research directions with a focus on agro-industrial applications in medium and large scale	2022	[14]
A review on thermal analysis of hybrid greenhouse solar dryer (HGSD)	2022	[213]
Solar dryers as a promising drying technology: a comprehensive review	2022	[214]
Design and analysis of different types of solar collector for solar air dryer: A review	2022	[215]
Systematic Literature Review on Machine Learning Predictive Models For Indoor Climate In Smart Solar Dryer Dome	2022	[216]
The indirect solar dryers with innovative solar air heaters designs: A review article	2022	[217]
A Comprehensive State-of-the-Art Review on the Recent Developments in Greenhouse Drying	2022	[218]

Table 6. *Cont.*

Title	Year	Ref.
Comparative energy-exergy and economic-environmental analyses of recently advanced solar photovoltaic and photovoltaic thermal hybrid dryers: a review	2022	[219]
Performance improvement and advancement studies of mixed-mode solar thermal dryers: a review	2022	[220]
A review study on recent advances in solar drying: Mechanisms, challenges and perspectives	2022	[221]
Solar drying of fruits—A comprehensive review	2022	[222]
A review of industrial food processing using solar dryers with heat storage systems	2023	[130]
Thermal energy storage systems applied to solar dryers: Classification, performance and numerical modelling: An updated review	2023	[127]
Designs, Performance and Economic Feasibility of Domestic Solar Dryers	2023	[92]
Assessing the suitability of solar dryers applied to wastewater plants: A review	2023	[223]
Performance enhancement techniques for indirect mode solar dryer: A review	2023	[224]
A review on the latest developments in solar dryer technologies for food drying process	2023	[225]
Progressive review of solar drying studies of agricultural products with exergoeconomics and econo-market participation aspect	2023	[226]
A review of solar drying technology for agricultural produce	2023	[227]
A review of the inflated solar dryer for improving the quality of agricultural product	2023	[228]
Photovoltaic-thermal systems applications as dryer for agriculture sector: A review	2023	[229]

5. Advantages and Limiting Issues

The utilization of solar energy to dehydrate food remains attractive in terms of energy efficiency and the wide range of products that are suitable for the technique (Figure 9).

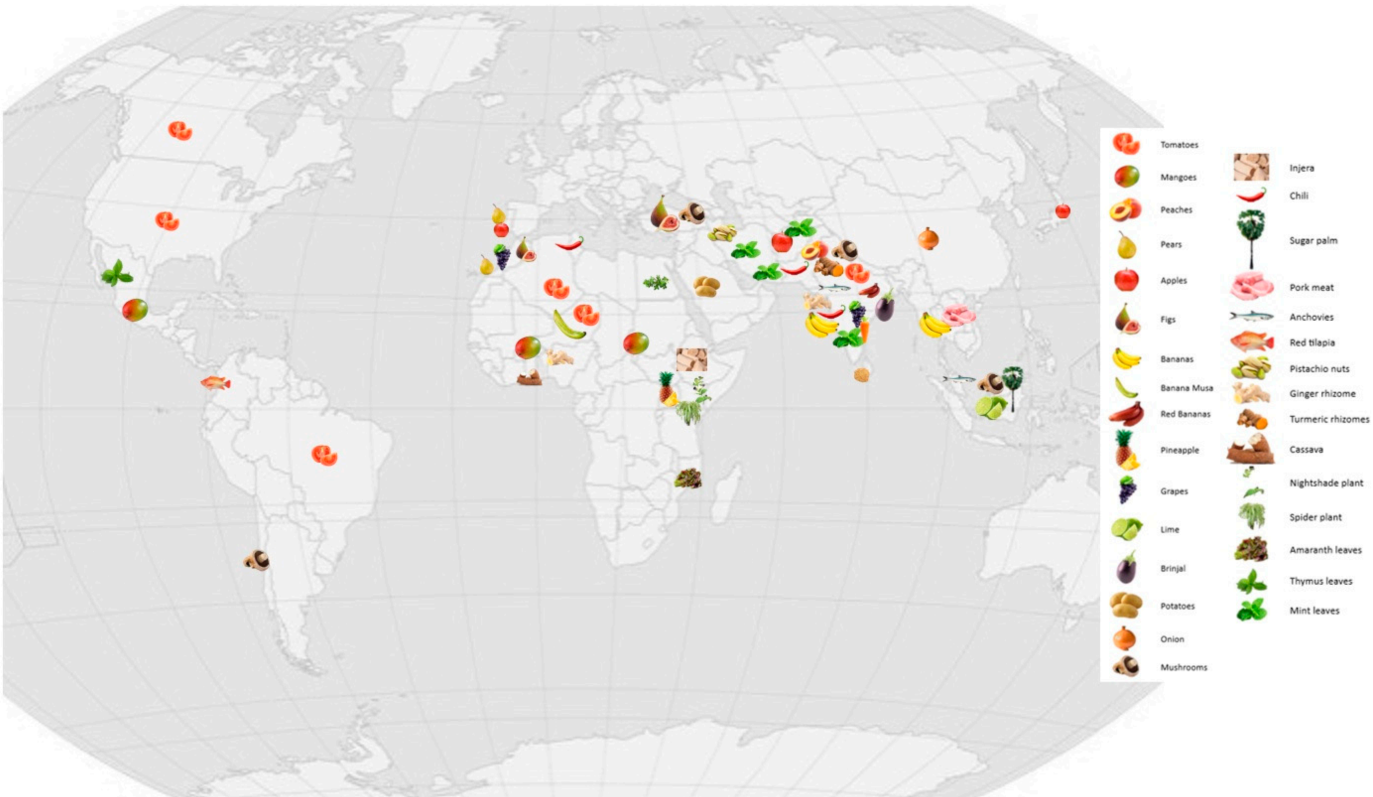
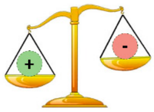


Figure 9. Overview of the distribution of the publications and type of dried products, all over the world, consulted in this review article.

Commonly, it is correct to refer to the principal advantages and disadvantages as follows in Table 7.

Table 7. Principal advantages/disadvantages of solar energy utilization in fresh products dehydration.

Advantages	Disadvantages
	
• Benefiting from solar energy as a renewable source for food consumption;	• Dependence on climatic variables;
• Possibility of utilization of recycled and low-cost materials;	• Could be less efficient compared with electrical dryers
• Does not require specialized labor and promotes the reduction in crop losses;	• Lack of investment in this type of processing
• Extending the preservation of food. Dried foods are also easier to store and transport, promoting convenience in consumption, which is valued in nutrition due to the absence of added sugar and other additives.	• For products requiring continuous drying, a backup heating system is necessary
• Contributes positively to sustainability and environmental preservation;	
• Improved food preservation, especially in underdeveloped countries where electricity could be unavailable;	
• Can generate income for small-scale producers and reduce losses;	

6. Conclusions and Final Remarks

Nowadays, especially with awareness of the 2030 Agenda for Sustainable Development global goals, food drying is a vital process for food preservation. Generally, dehydration is a good solution, but concerns related to energy consumption and fossil fuels persist. The use of solar energy, once widely employed in the past, is regaining importance. This trend is evident in the number of studies considered in our review article. Performance, design parameters, location, atmospheric conditions and type of crop are principal factors taken into consideration when choosing the best mode for drying purposes. The articles aim to synthesize the findings from various studies, identify trends in the literature and provide insights and recommendations for further research and development in the field of solar drying.

Our paper reviewed the designs and mechanisms of various types of solar dryers, with a main focus on heat transfer, air movement and types of chambers. All the dryer layouts have advantages and disadvantages, but commonly, mixed-mode and hybrid types are more efficient in terms of time compared with direct and indirect modes. However, they are not entirely sustainable. Active circulation takes less time and yields better final products than open-air and natural circulation, although it represents limitations in terms of product quantity. For large-scale crop drying, the greenhouse type is the best method, but it requires more space.

The cited review articles are a valuable resource for researchers and practitioners interested in understanding the current state of knowledge and advancements in solar drying technologies and applications.

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Glossary

Nomenclature

PW—petawatts
UV—ultraviolet
W—watt
W/m^2—watts per square meter

Abbreviations

CFD—computational fluid dynamics
CHP—chemical heat pump
DMTD—direct type solar dryer
DSD—direct solar drying
FCD—forced convection dryer
HAD—hot air dryer
HGSD—hybrid greenhouse solar dryer
HPD—heat pump integrated dryer
HSD—hybrid solar drying
IFCSD—indirect forced cabinet solar drying
ISD—indirect solar drying
LHS—latent heat storage
LPG—Liquefied Petroleum Gas
MMTD—mix-mode type solar dryer
NCD—natural convection dryer
NCDT—natural convection and direct type solar dryers
FAO—Food and Agriculture Organization
CO_2—carbon dioxide
OSD—open sun drying
DNI—direct normal irradiance
PCM—phase change material
PV—photovoltaic
PV/T—photovoltaic thermal
SGD—solar greenhouse dryer
SHS—sensible heat storage
STD—solar tunnel dryer
SUS—steel use stainless
TCES—thermos-chemical energy storage
TES—thermal energy storage

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