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Photovoltaic-thermal systems applications as dryer for agriculture sector: A review

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ABSTRACT

In this paper, the literature writing on the use of photovoltaic thermal air collectors (PV-T) and integrated greenhouse drying systems for PV-T air collectors as a mean to reduce fossil fuel consumption and reduce global warming is reviewed. Countries with limited electricity sources, solar drying is an effective way to preserve crops for long-term use. There has been evidence that PV-T air collectors are superior to individual PV modules for storing energy when it comes to controlling drying parameters. The review will offer valuable insights and data that can aid scientists and researchers in the creation and improvement of thermal models for combined solar systems. The review will present a detailed analysis of the current state of knowledge in the field of combined solar systems, including the latest advancements, trends, and challenges. It will also identify gaps in the existing research and suggest potential avenues for future investigation.

1. Introduction

In a PV-T system, the combination of photovoltaic and solar thermal components captures and converts solar energy into electricity and heat [1]. With their ability to provide hot water or air and electricity, PV-T systems are increasingly popular (see Fig. 1(b)), thereby reducing energy costs and helping to reduce carbon dioxide emissions. It is relatively easy to install PV-T systems at homes, commercials, and industries, and they require little maintenance [2]. Their high efficiency and reliability make them an excellent source of clean, reliable energy. Multiple strategies were employed by the creators and producers of PV-T systems to chill their apparatuses. There are different types of cooling systems such as air cooling [3,4], water cooling [5,6], nanofluid cooling [7,8], phase change material (PCM) cooling [9,10], nanofluid and nano-PCM cooling [11,12]. A variety of base liquids, such as water, oil, and ethylene glycol, was used as cooling agents [13,14,15]. Nanofluids were tested with different metals and non-metals nanoparticles and their oxides [16,17,18]. In order to mix these particles with the base fluid, advanced techniques were used [19,20]. There were many types of phase change materials used, though paraffins with varying melting points were most commonly used [21,22,23]. In the past decade, thousands of experiments and theoretical studies have yielded PV-T systems with extremely high performance. Comparing

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these systems to PV systems, these systems continue to show superior productivity even in conditions of extreme temperatures and radiation intensity [5,24].

A variety of applications can benefit from PV-T systems, including residential and commercial buildings, solar water heating, industrial process heat, solar desalination, agriculture, and solar cooling [25]. It is possible to combine PV-T systems with other renewable energy sources such as wind and biomass to form hybrid systems [26]. Electric vehicles are another application of photovoltaic-thermal systems [27].

PV-T systems are being increasingly utilized in agriculture to reduce energy costs and increase crop yields [28]. PV systems use energy from the sun to generate electricity, while thermal systems take advantage of the sun's heat to generate hot water for agricultural or other purposes [29]. These systems can be used to power irrigation systems, such as pumps and sprinklers, as well as providing light and heat for greenhouses and livestock buildings. They can also be used to power sensors, monitoring systems, and other technologies used in precision agriculture. PV-T systems are becoming increasingly popular in agricultural applications as they are cost-effective, reliable, and require little maintenance [30]. PV-T heating agriculture applications involve benefit from the sun's rays to generate heat that can be used in agricultural operations, such as crop drying, greenhouses, and livestock barns. PV panels convert sunlight into electrical energy, which is then used to power a thermal storage system [31]. This storage system can then be used to generate heat for various applications. For example, in crop drying, the heat generated from the thermal storage system can be employed to dry crops faster and more efficiently [32]. In greenhouses, the heat can be used to maintain a consistent temperature throughout the year, allowing for optimal growing conditions. In livestock barns, the heat can be used to provide a comfortable environment for animals. PV-T systems can also be used to preheat water for irrigation purposes, significantly reducing energy costs for farmers [33].

This study aims to revise applying PV-T systems in dryers for agriculture sector with more focus on heating applications. By providing this information, the paper provides researchers better understanding the underlying principles and mechanisms of combined solar systems and to develop more accurate and efficient thermal models. Design optimization can be accomplished using these models, operation, and performance of combined solar systems, leading to increased energy efficiency, cost-effectiveness, and sustainability.

Overall, combined solar systems experts will find this review a valuable resource, providing them with the knowledge and tools necessary to make significant advancements in this important and rapidly evolving area of research.

2. Literature survey

Much research recently conducted to investigate applications of PV-T for agriculture sector [35,36,37,38,39,40]. El-Sebaii et al. (2013) [41] reviewed PV-T systems for agricultural applications. This article provided an overview of diverse PV-T configurations, the types of agricultural uses, and these systems' performance. It also discusses the potential of PV-T systems for agricultural applications and their economic viability. The authors conclude that PV-T systems offer multiple benefits such as better energy efficiency, cost savings, improved crop yields, and environmental benefits. Further, they suggest that PV-T systems could be a viable option for agricultural applications if economic and environmental incentives are offered.

An integrated PV-T greenhouse system has been developed by Park (2017) [42]. In addition to reducing energy costs, the system maximizes energy efficiency and benefits the environment. The PV-T system combines a PV unit linked to a "flat collector panel" (FPC). The system utilized both PV module and FPC to generate electricity and heat, respectively. The system was tested under different conditions to determine its performance and effectiveness. The system was able to generate electricity of about 14.4%, and thermal efficiency up to 53.4%. The authors concluded that their system was suitable both in terms of cost and environment. This study offers an important basis for the advancement of PV-T systems for greenhouses.

Suresh et al. (2023) [43] reassessed the current state of the art in "Natural Energy Materials" and "Storage Systems" for solar dryers. The paper highlights the potential of using natural energy sources for drying agricultural products and the importance of "energy storage systems" to ensure the uninterrupted operation of solar dryers. The authors discuss various natural energy materials and storage systems, including "Phase Change Materials (PCMs)", "Thermal Energy Storage (TES)", and biogas. An overview of the latest

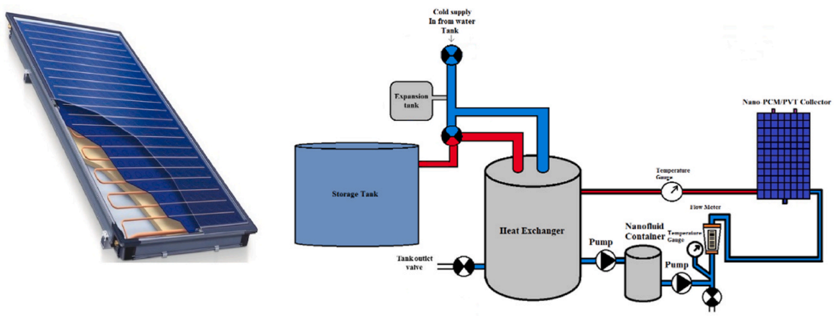

Fig. 1. PV-T (a) collector, (b) system [34].

research on the use of these materials and systems in solar dryers was also provided in this article. The paper includes a detailed analysis of the advantages and limitations of each natural energy material and storage system. The authors found that PCMs are the most promising natural energy material for solar drying. They have the ability to store a large amount of thermal energy, and releasing it when needed, making them ideal for use in solar dryers. The paper also discusses the challenges associated with using PCMs, such as their low thermal conductivity and high cost. Finally, the authors reviewed the use of biogas as a natural energy source for solar dryers. Biogas is produced from organic waste and can be used as a fuel source for the dryer. The paper includes a discussion of the challenges associated with biogas production and its use in solar dryers.

The effectiveness of PV-T systems in terms of their design was evaluated by Touti et al. [44] using a combination of experiments and calculations. The authors conducted experiments on different PV-T designs and used numerical simulations to analyze their performance. A variety of design elements, including the thickness and material of the absorber plate as well as the space between the photovoltaic cells and the absorber plate, were examined to determine how PV-T systems function. Also, system execution could be influenced by the photovoltaic cells and absorber plate. Using their findings, the authors concluded that the thickness and material of the absorber plate greatly influence thermal performance. Thicker and higher thermal conductivity materials lead to better thermal performance. Thermal performance is diminished when the gap between the PV cells and absorber plate is widened. The electrical output of PV-T with a tighter spacing between PV cells and absorber plate, on the other hand, was greater. However, the decrease in thermal performance associated with the smaller spacing resulted in an overall reduction in the system's energy efficiency.

In a German dairy farm, Hosouli et al. (2023) [45] examined the performance of a solar PV-T system. An in-depth analysis of the system's electrical and thermal performance, including energy production and efficiency, was completed by the authors. By calculating payback periods and internal rates of return, a financial feasibility was also determined for the PV-T system. An annual power generation of 20,518 kWh and 35,550 kWh was determined for the PV-T system. In total, 36% of the energy output was electrical, while 64% was thermal. The system had an overall efficiency of 56.3%. The proposed PV-T systems can be paid back within 7.5 years, and an internal rate of return of 9.2%, providing evidence of the system's economic viability. In particular, PV-T systems have potential in the dairy industry, according to the study. Using PV-T systems on dairy farms can reduce the dairy farms' dependence on grid electricity and provide a significant amount of energy.

A PV-T system was installed in a solar greenhouse by El-Ghamrawy (2016) [46] to investigate its outcomes. In this system, two photovoltaic modules were linked in parallel, a flat plate collector was used, as well as a fan and a heat exchanger. The test setup was put in a closed chamber with a simulated environment. The system had the ability to diminish the temperature inside the chamber by as much as 3.5 °C and the relative humidity by up to 5.5%. The system efficiency was ranged from 6.5 to 12.5%. It was also noticed that the cooling performance increased with rising ambient temperature and wind velocity. The system offered a cooling capacity of up to 17 W and a coefficient of performance of up to 1.1. An analysis of the theoretical results was conducted, and they were found to be in agreement with the experimental results.

Li (2017) [47] provided an overview of the use of PV-T systems in agricultural production related to cold storage. Various advantages and disadvantages of these systems were discussed in the study, as well as the current utilization of them in China and other countries. It was found that PV-T systems boast high energy efficiency, low cost, and zero emissions, and are mainly used in the food and beverage industry and greenhouses. However, there are only a few cases of PV-T systems being used in cold storage. In order to make PV-T systems more common in cold storage, additional research and study should be conducted. This will reduce energy consumption and improve energy efficiency.

In [48], an evaluation of PV-T systems for agricultural purposes is conducted. It examines the capacity for energy savings, cost efficiency, and ecological advantages of PV-T systems. Additionally, their thermal collectors, substances, and control techniques are scrutinized. Examining the existing research on the matter, the review reveals that PV-T systems have already been applied to a variety of agricultural uses, such as greenhouses, livestock buildings, and crop drying systems. In conclusion, the study demonstrated that PV-T systems can be a successful and economical way of diminishing energy usage and environmental contamination in the agricultural industry.

Abdulhadi et al. (2015) [49] conducted research into the capacity of an integrated PV-T system to cool greenhouses located in Jordan. Using a numerical simulation model, the study determined that a PV-T system with a collector area of 49.2 m^2 managed to reduce the maximum daily temperature inside the greenhouse by 6.2–7.4 °C, providing an efficient cooling method. Furthermore, the system had the potential to generate an extra 31.3 kWh/m^2/year, highlighting the additional advantages to using a PV-T system.

Using an agricultural PV-T system [50], showed that it was capable of supplying both electricity and hot water, with a maximum electrical efficiency of 37%. It was also determined that the use of the PV-T system resulted in a reduction of electricity costs by up to 30% and an increase of thermal energy output by up to 20%. As a whole, their research concluded that using PV-T systems in agricultural applications is feasible.

In the research conducted by Bhattacharya (2007) [51], an optimization algorithm was used to work out the perfect set-up for an integrated PV-T system for greenhouses. An inquiry into how different elements, such as the slant of the panel, thermal saving, and the amount of PV boards, influence the outcome, revealed that 30° was the optimal panel tilt angle, while thermal storage could significantly enhance the system's total effectiveness. Surprisingly, the study also found that increasing the number of PV panels did not necessarily lead to a higher efficiency. This information is incredibly valuable when constructing greenhouses with PV-T systems.

Hamdan (2009) [52] evaluated practically a PV-T system in greenhouses. This system combines the capabilities of a photovoltaic panel to produce both electricity and heat. The experiments revealed that the PV-T system generated 2.7 kW of thermal energy and 2.7 kW of electrical energy. Furthermore, the system was more efficient than either a PV panel or a standard heating system. The authors therefore suggested that the PV-T system is a viable and efficient energy source for greenhouses.

In Kuwait, PV-T systems were used to cool a greenhouse during the summer [53]. There were three components to this system: a solar panel, a heat sink, and a fan. With an efficiency of 44.7%, the PV-T system produced 1.45 kW of electricity and 2.51 kW of thermal energy with a maximum temperature drop of 3.2 °C. The PV-T system is clearly an effective method of cooling greenhouses.

The following points can be considered as the most important features of Table 1.

- PV-T efficiency is primarily dependent on the system's temperature, the kind of PV cells employed, the design of the module, and the integration of the thermal and PV components. In general, the higher the temperature of a system, the greater its thermal efficiency. A PV cell's type also influences the efficiency of the system, the module's design, and the incorporation of the thermal and PV components [62,63].
- The effectiveness of PV-T systems differs according to the kind of system, the energy source, the size of the system, its situation, and the amount of sunlight available. PV systems usually have better efficacy than thermal systems since they are able to change sunlight into electricity directly. A thermal system, on the other hand, uses the sun's rays to heat up a liquid, which then generates electricity. The efficiency of any PV-T system can be amplified by installing components such as solar tracking systems, optimized module and system designs, and materials that absorb and release more energy such as PCM (Paraffin wax as an example) [64,26].
- The temperature fluctuation for PV-T systems can be caused by a range of factors. The temperature changes of PV systems rely on the ambient temperature, the quantity of direct sunlight, and the kind of PV material utilized. For thermal systems, the temperature variation is dependent on the ambient temperature, the amount of direct sunlight, the type of thermal material used, and the amount of insulation in the system. Additionally, the orientation of the solar panels can also affect the temperature variation for both PV and thermal systems [65,66].

This paper aims to offer a broad overview of PV-T hybrid solar collectors emphasizing the agricultural sector. The background of the PV-T system is explored, such as its origin, idea and advantages. In addition, the different types of PV-T systems are described according to various strategies. Finally, the primary uses of the system in the agricultural industry are looked into.

3. PV-T systems principles and classification

3.1. Solar cell and photovoltaic module

A solar cell and photovoltaic module are both key elements of a solar power setup, as illustrated in Fig. 2(a) [67]. Electricity is generated by the conversion of light energy into photovoltaic modules. Photovoltaic modules combine many solar cells into one unit, as seen in Fig. 2(b). Together, they are the key elements in harnessing the sun's energy and providing the world with clean, renewable energy [68,69,70].

Photovoltaic technology classified into inorganic, organic, and hybrid as illustrated in Fig. 2© [71]. Inorganic PV technology is based on inorganic semiconductor materials such as silicon and cadmium telluride. These materials are most commonly used in crystalline or thin-film solar cells [60]. Crystalline solar cells offer higher efficiency rates and are made of large, single-crystalline silicon wafers. Thin-film solar cells are less efficient but also less expensive and require less energy to produce than crystalline solar cells [72]. Organic PV technology is based on organic semiconductors such as polymers and small molecules. This type of technology offers low-cost, lightweight, and flexible solutions [73,74]. Organic PV cells are less efficient than inorganic PV cells, but may be more suitable for certain applications. Hybrid PV technology combines the advantages of both inorganic and organic PV technologies. These systems combine inorganic materials with organic materials to create a hybrid device. Hybrid PV systems offer the efficiency of inorganic materials and the flexibility of organic materials [75].

The current-voltage characteristics of a solar cell, illustrated in Fig. 2(d) [76,77], are an essential part of understanding and optimizing the PV systems' efficiency. These I–V characteristics are useful in assessing the efficiency of a solar cell and the power output that it can achieve at different levels of illumination. In this article, we explain the basics of solar cell I–V characteristics and

Table 1
Examining the similarities and differences of PV-T systems in the literature.

Ref. No.	Thermal Efficiency (%)	Electrical Efficiency (%)	Temperature (°C) p: Peak, r: Reduced
[41]	80.0	21.2	81.8 p
[42]	50.0–52.0	17.0–19.0	20.0 r
[46]	55.0	15.0	10.0 p
[47]	20.3–30.6	13.7–15.2	2.0–20.0 r
[48]	63.0	18.0	65.0 p, 5 r
[49]	62.2	16.8	45.0 p, 6.0 r
[50]	70.1	12.7	45.3 p
[51]	50.0–64.0	10.0–15.0	30.0–45.0 p
[52]	85.0	14.7	54.0 p
[53]	22.1–25.0	17.6–20.8	39.9–41.3 p
[54]	53.4–62.4	17.5–22.2	25.0–55.0 p
[55]	1.3–10.8	5.2–12.9	25.0-60–0 p
[56]	28.0	18.0	55.0 p
[57]	28.3	7.1	47.4 p
[58]	67.0	20.0	20.0-30–0 p
[59]	80.0	20.0	20.0 p
[60]	41.3–51.3	6.5–10.8	30.0–90.0 p
[61]	60.0–80.0	15.0–20.0	40.0 p

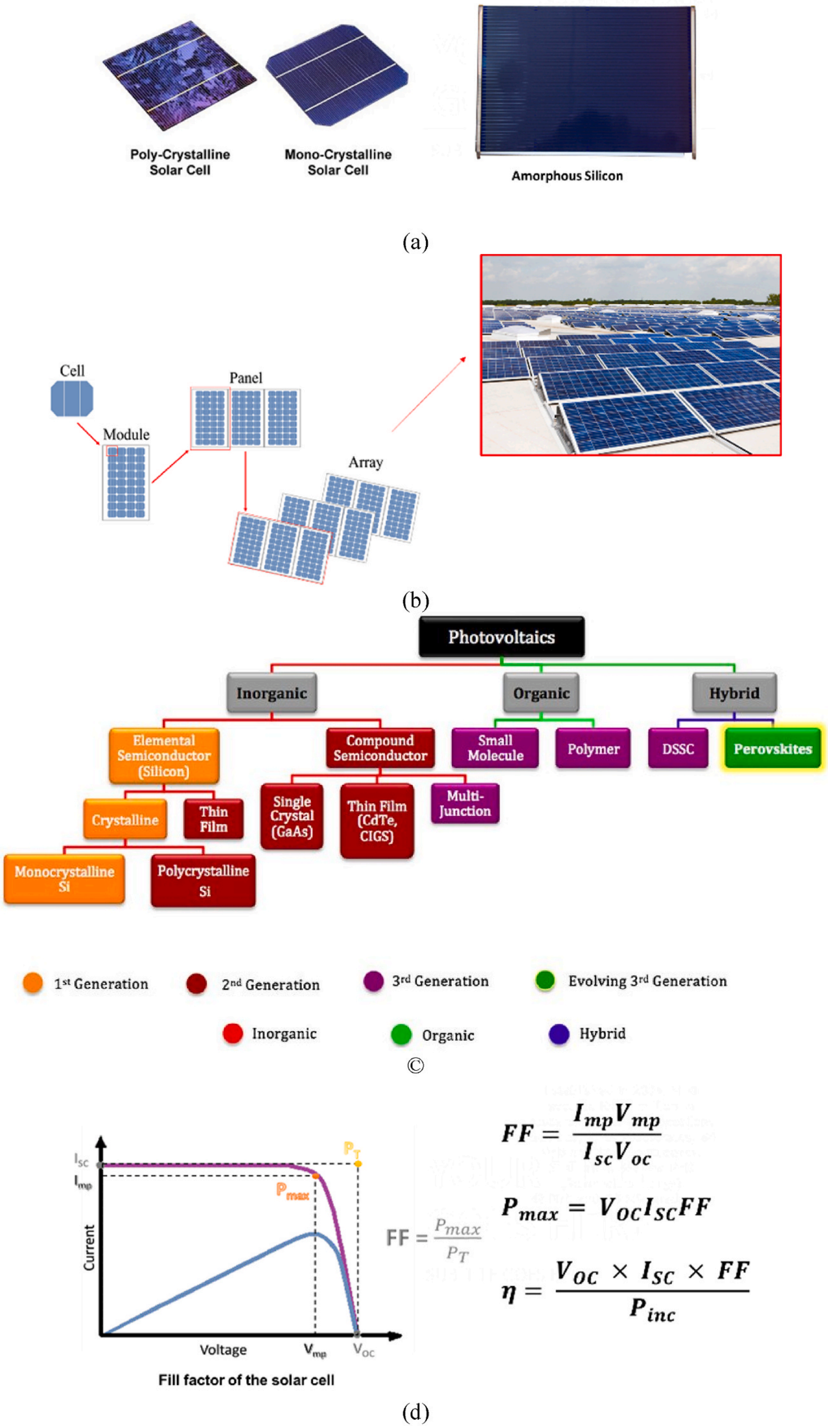

Fig. 2. (a) solar cell, (b) photovoltaic module, (c) PV classification, (d) I–V characteristics.

how they can be used to optimize solar cell performance.

3.2. Solar thermal

It is possible to heat water using solar thermal energy, create electricity, and run various industrial operations like air conditioning. Solar thermal technologies are cost-efficient, provide energy independence, and reduce the environmental impact of electricity generation. Solar thermal energy can be deployed on the residential, commercial, and industrial scales [78,79].

Solar thermal collector are classified based on the operation mode into (see Fig. 3(a)) [80,81].

1. No external power is needed for passive solar thermal collectors, which are the most basic and widespread kind of solar thermal collector. Heat is transported from the sun to the collector through natural convection and conduction. Flat-plate collectors FPC and evacuated tube ET collectors are two common examples of passive solar thermal collectors [82,83].
2. Active Solar Thermal Collectors: These use an external energy source, such as a fan or pump, to move the heated air or liquid through the collector. This allows for more efficient energy transfer and makes them suitable for use in larger scale applications, such as district heating systems. Examples of active solar thermal collectors include forced-air collectors, thermosiphon collectors, and concentrating collectors [84,85].

Also, the thermal collectors classified based on the achieved temperature into [86,87].

1. Low-Temperature Collectors: These are designed to heat water or other fluids to temperatures up to 180 °F (82 °C). They are usually used for domestic hot water heating and pool heating. Thermosiphons, evacuated tubes, and flat plate collectors are among the types of collectors that work at lower temperatures [88].
2. Medium-Temperature Collectors: Such collector are designed to heat water or other fluids to temperatures up to 600 °F (316 °C). Medium temperature collectors are typically employed for industrial operations, including heating and cooling of spaces and providing process heat. Examples of this type of collector include forced-air and concentrating collectors [89].
3. High-temperature collectors are designed to heat water or other fluids to temperatures greater than 600 °F (316 °C). They are usually used for industrial processes, such as steam production and electricity generation. Examples of high-temperature collectors include parabolic troughs and solar towers [90].

It is possible to determine the energy of a solar thermal collector using a formula that depends on the collector's size, the average air temperature, the average collector's temperature and the efficiency. This equation can be used to make this calculation [91,92]:

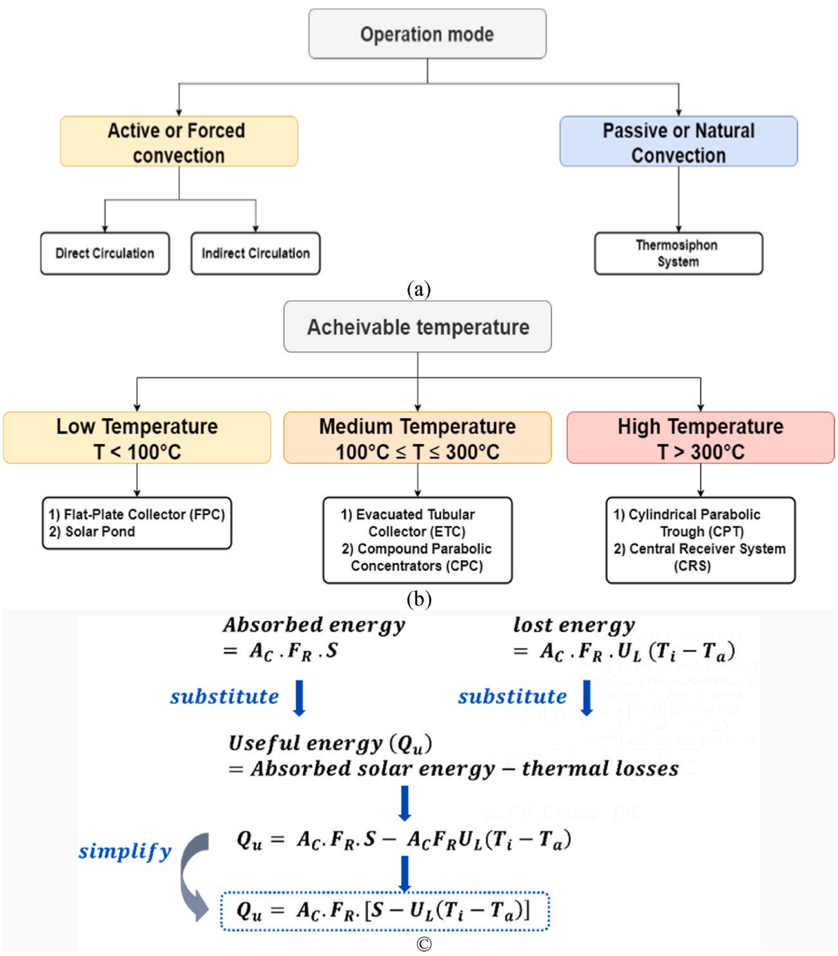

Fig. 3. Solar thermal collector classification based on (a) operation mode, (b) achieved temperature, and (c) energy calculations.

$$\eta = \frac{Q_u}{I_T.A_C} \tag{1}$$

$$Q_u = A_c\left[S - U_L\left(T_{pm} - T_a\right)\right] \tag{2}$$

$$S = (\tau.\alpha)_{av}.I_T \tag{3}$$

Fig. 3© illustrate the calculate procedure of thermal energy for the solar collector.

3.3. Photovoltaic-thermal systems

In these systems, solar PV and solar thermal technology are used to harness the power of the sun [81]. PV-T systems are a viable and efficient way to produce electricity and hot water, making them an ideal solution for homes and businesses that need to reduce their energy costs and increase sustainability [93]. PV-T systems are relatively easy to install and maintain, and can be installed on almost any roof or ground-mounted system. This introduction will cover the basics of PV-T systems, including the technology behind them, their advantages, and disadvantages, and how they work.

A system's overall performance is evaluated by adding together the efficiencies, which is called $\eta_{combined}$ (total efficiency combined) [94]:

$$\eta_{combined} = \eta_{th} + \eta_{el} \tag{4}$$

The following formula calculates the conventional flat plate solar collectors' thermal efficiency (η_{th}):

$$\eta_{th} = \frac{Q_u}{I_{(t)} * A_c} \tag{5}$$

$$Q_u = A_c F_R[S - U_L(T_i - T_a)] \tag{6}$$

A PV module's temperature-dependent electrical efficiency (η_{el}) can be expressed as follows [95]:

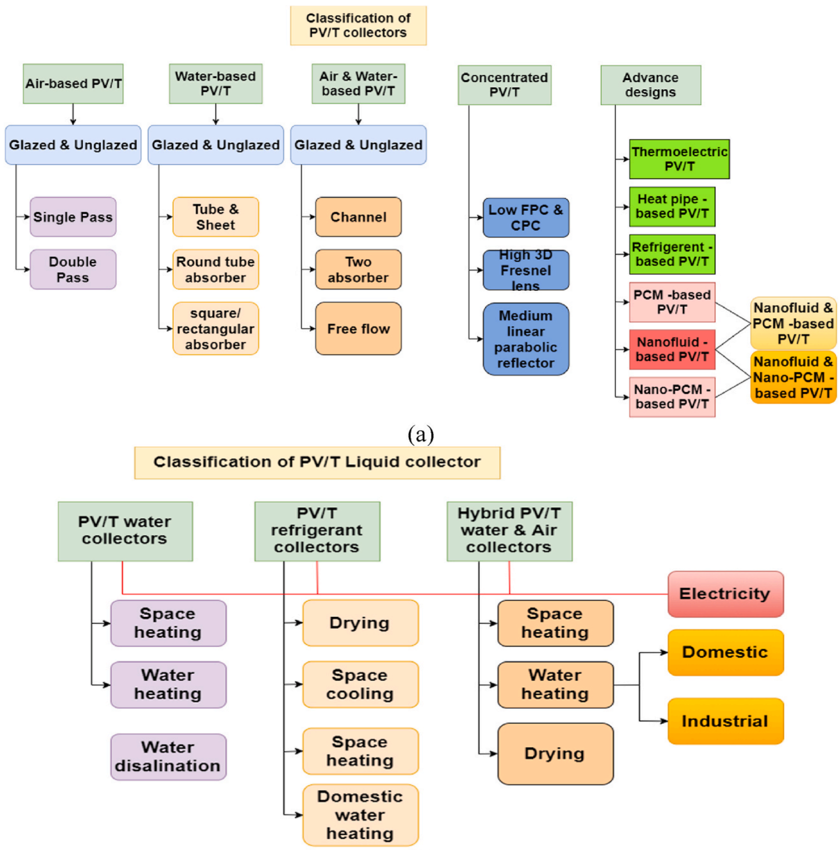

Fig. 4. PV-T based on (a) collector, (b) liquid.

$$\eta_{el} = \eta_r \left(1 - \beta * \left(T_{pm} - T_r\right)\right) \tag{7}$$

PV-T classified into active and passive. Pumps, fans or other mechanical components are used to circulate fluids and transfer heat from the PV to the thermal system in active PV-T systems [96]. Passive PV-T systems employs heat transfer by radiation and natural convection from the PV panel to the thermal system. There are several types of PV-T systems, as illustrated in Fig. 4(a). In these systems, there are three main types of collectors: "Flat Plate Collectors FPC" (use air, water, or air/water), "Concentrating Collectors CC", and "Hybrid Collectors HC" (advance collectors).

A flat plate collector is the most widely used collector in PV-T systems (FPC). They consist of a flat plate with a dark-colored absorber that is exposed to sunlight. FPCs are relatively simple and cost-effective, but they are not as efficient as other types of collectors.

Concentrating collectors are designed to focus the sunlight onto a smaller area, using mirrors or lenses. This results in a higher concentration of solar radiation, which can be used to generate more electricity or heat. Concentrating collectors can be further divided into two subcategories: parabolic trough collectors and dish collectors.

Parabolic Trough Collectors: These collectors use curved mirrors to focus sunlight onto a receiver tube that contains a fluid, which is heated by the concentrated solar radiation. The hot fluid is then used to generate electricity or to heat water or air.

Dish Collectors: Dish collectors use a dish-shaped mirror to concentrate sunlight onto a receiver, which can be either a photovoltaic cell or a thermal receiver.

Hybrid Collectors: Hybrid collectors combine the features of both flat plate and concentrating collectors. They typically consist of a flat plate with a concentrator that focuses the sunlight onto a smaller area of the absorber. This results in higher thermal and electrical efficiency than flat plate collectors, while still maintaining lower costs compared to concentrating collectors. Overall, the choice of collector type depends on the specific application, as well as factors such as cost, efficiency, and scalability.

Fig. 4(b) shows how PV-T systems can also be classified based on what type of liquid they use. Thermal energy generated by the PV-T system is collected and transferred by the liquid. PV-T systems use three main liquid types: air, water, and other liquids. Air-based PV-T Systems A PV-T use air as the working fluid. After passing through a heat exchanger, the air is circulated after being heated by solar radiation. Where it transfers its thermal energy to a fluid, which can be water or another liquid. A PV-T are relatively simple and cost-effective, but they are less efficient than other types of systems and are better suited for low-temperature applications.

Water-based PV-T Systems W PV-T use water as the working fluid. The water is heated by the solar radiation and then circulated through a heat exchanger, where it transfers its thermal energy to a fluid, which can be air or another liquid. W PV-T are more efficient than A PV-T and can be used for both low and high-temperature applications.

Other liquid-based PV-T systems: As a working liquid, some PV-T systems use liquids other than air or water. These liquids can be organic fluids, such as propylene glycol, or inorganic fluids, such as molten salts. Also, nanofluid with different nanoparticles could be used to enhance thermal conductivity. These fluids have different properties, such as higher boiling points and lower freezing points, which make them suitable for high-temperature applications. Other liquid-based systems are more complex and expensive than air or water-based systems but can achieve higher thermal efficiencies.

Overall, the choice of liquid depends on the specific application (electricity, domestic, and industrial) and the desired temperature range.

4. PV-T systems applications

A PV-T system is a type benefits from solar energy to produce electrical power using PV technology combines with solar thermal energy to provide a range of applications. This technology has many uses in applications such as air conditioning, ventilation, heating and power generation [97]. Various electrical and thermal devices can be powered by PV-T systems. This type of system is becoming increasingly popular due to its cost-effectiveness and ability to reduce energy consumption. It also has a number of environmental benefits, including a reduction in carbon emissions and a decrease in the amount of non-renewable energy sources used. In this article, we will discuss the applications of PV-T systems and the advantages they offer [98,99]. The main PV-T applications are.

1. Power Generation: Generally, PV-T systems produce electricity that can be used for both commercial and residential purposes.
2. Air Conditioning: PV-T systems can be used to cool, ventilate and heat buildings, reducing energy consumption.
3. Heating: PV-T systems can supply hot water and space heating.

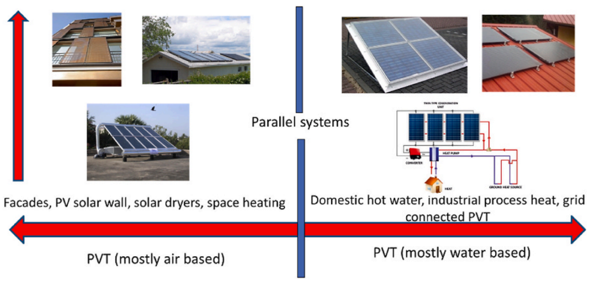

Fig. 5. Integration of PV-T system applications.

4. Agriculture: PV-T systems can supply energy for agricultural activities, such as heating and drying, pumping water and powering machinery.
5. Transportation: PV-T systems can power electric vehicles.

PV-T integration involves the incorporation of both PV and thermal elements into one integrated system as shown in Fig. 5. The purpose of this system is to provide cooling, heating, and electricity to a building while utilizing the most energy possible [100,101]. PV-T systems typically use a combination of PV cells, thermal collectors, and a heat pump to capture and store the energy generated by the sun. Optimizing the PV-T system maximizes its efficiency. In order to achieve this, photovoltaic, thermal, and heat pump components are combined in a way that generates the most energy at the lowest cost. The optimization of the system can involve several different elements, such as: system sizing, design optimization, thermal storage, and cost optimization. Additionally, the system can also be designed to integrate solar energy with other energy sources, such as geothermal or wind power, to further optimize the efficiency of the system [33,102].

5. PV-T systems as dryer for agriculture applications

PV-T systems are becoming increasingly popular for agricultural applications because they can provide an efficient and cost-effective way to power irrigation systems, greenhouses, or other agricultural operations. The electricity generated can be used to run pumps and other equipment, while the thermal energy can be employed in space heating and crop drying. PV-T systems are also becoming popular because of their environmental benefits, as they reduce the need for fossil fuels and can help reduce a farm's carbon footprint.

PV-T collectors are an ideal way to dry agricultural products such as grains and fruits. The PV-T collector may be used in a variety of ways, including direct drying, indirect drying, and forced-air drying [103,104]. In direct drying, the solar radiation is converted into thermal energy, which is used to heat the air and agricultural product directly. In indirect drying, electricity is produced by PV modules and then this electricity main function is to dry the product by operating a blower or fan. In forced-air drying, the air is heated directly and then circulated over the agricultural product [105]. PV-T collectors are also used for drying hay and silage for animal feed, as well as for drying coffee, tea, nuts, and spices. By using PV-T collectors, farmers can reduce the cost of agricultural production and increase their yields.

Reference [106] evaluated a solar PV-T air collector drying system performance. The researchers used a flat solar collector attached to a photovoltaic panel and a fan, which is used to dry materials such as corn, wheat and soybeans. The system achieved a drying efficiency up to 87.17%, and that the drying rate increased as the air temperature, mass flow rate, and solar radiation intensity increased. The study also found that the drying rate decreased with increasing relative humidity. Materials can be dried effectively and efficiently using the PV-T air collector drying system based on the research results.

Reference [36] studied the results of a drying system using a PV-T-assisted heat pump. Through theoretical and experimental investigations, the authors analyze the performance of the drying system in terms of energy efficiency, drying time, and the effect of different parameters on the drying efficiency. They also conduct a simulation study to evaluate the effect of different operating conditions and PV-T panel parameters on the system performance. Results show that the drying system is effective in reducing drying time and energy consumption, with the highest energy efficiency of 92.8% under the optimal operating conditions. The findings of this study can help optimize the design and operation of PV-T assisted heat pump drying systems for improved efficiency and sustainability [107].

Reference [108] examined MHP- PV-T systems' performance in Chinese greenhouses in winter, both inside and outside of the greenhouses. It uses mathematical modelling and simulation to analyze the performance of the systems and their effects on the environment. The results indicate that the performance of the MHP- PV-T systems inside the greenhouse was significantly better than outside the greenhouse, with overall energy production being higher and the greenhouse temperature being more stable. The study also found that the systems had a better shading performance inside the greenhouse, leading to an increase in the greenhouse temperature and a reduction in the heat loss during winter. The results suggest that the MHP- PV-T systems should be installed inside greenhouses in order to maximize their performance and minimize the environmental impacts.

Reference [109] presented the results of an experimental investigation of a drying system benefits from PV-T air collector and wind turbine. The system's drying performance, energy conversion efficiency, and energy storage capacity were evaluated and analyzed. The study conclusions indicated that the system's energy conversion efficiency was raised to 84.02%, and the drying rate was increased due to the used of PV-T air collector. The system also had a high energy storage capacity, with a maximum storage capacity of up to 2.12 kWh. The study demonstrated the potential of the hybrid drying system for efficient energy conversion and storage.

Reference [105] examined the use of PV for water pumping in dry land agriculture and the potential for carbon sequestration. The authors analyze the cost-effectiveness of PV systems in comparison to diesel pumps and present a case study from India. They conclude that PV systems are economically viable and can provide significant environmental benefits, including carbon sequestration.

As a possible substitute for standard drying techniques, a hybrid PV-T supported desiccant with HA-IR drying system (HPIRD) was studied [85]. In order to replicate the HPIRD system's performance, a computer simulation model was used. The simulation results showed that the HPIRD system had a significantly higher drying rate and energy efficiency than traditional drying methods. The HPIRD system was found to be an effective method for drying food and by-products by the authors.

A hybrid PV-T greenhouse dryer was evaluated in Ref. [110] for drying grapes. Through an experimental study, the authors found that the dryer was able to reduce the drying time of grapes by 50%.

Reference [111] evaluated a PV-ventilated solar greenhouse dryer performance, which was used to dry peeled longan and banana.

The paper includes an experiment which monitored the drying process of both fruits as well as a computer simulation which compared the dryer resulted performance with a conventional dryer. PV-ventilated solar greenhouse dryers exhibited significantly shorter drying times for both types of fruits than traditional dryers, and fruits dried in solar greenhouse dryers had significantly lower moisture contents than conventional dryers. The paper concludes that the PV-ventilated solar greenhouse dryer is a promising energy-saving device for drying of peeled longan and banana.

In China, In Reference [28] a study was conducted to evaluate the financial and social impacts of photovoltaic (PV) greenhouse systems. Integrated systems in the local community were found to have a positive economic impact, resulting in improved income levels and access to employment. Additionally, the study revealed that the systems had a positive social impact, leading to increased energy access, improved air quality, and reduced greenhouse gas emissions. The paper concluded that integrated PV and agricultural greenhouses systems can be an effective way to improve both economic and social conditions in China.

A study by Ref. [112] examined the feasibility of providing dairy farms with “combined heat and power” (CHP) using spectral-splitting hybrid PV-T. In order to model the PV-T system, component-based methods were employed, and effects of modifying the system’s design were examined. Based on the results of the study, it was concluded that the system was highly effective and could bring considerable economic benefits to the dairy farm. The authors concluded, therefore, that spectral-splitting hybrid PV-Ts are suitable for providing CHP in dairy farms.

Akpinar and Kavak [113] experimented the solar drying of mint leaves under open sun, and modelled and analyzed their performance. The study was conducted in a solar dryer with a natural convection air flow and an open sun drying system. The results showed that the drying process was faster in the open sun drying system, but the solar dryer was more effective in preserving the colour, flavour, and essential oils of the mint leaves than the open sun drying system. The results also showed that the drying rate decreased with increasing initial moisture content, and that the drying times were decreased when the air temperature and relative humidity decreased.

Reference [114] reviewed the state-of-the-art of solar-energy drying systems and their potential applications. It analyses the various techniques used for utilizing solar energy for drying purposes and their advantages and disadvantages. The authors compare the different types of solar dryers, including FPC and ET collectors, solar tunnel dryers, and desiccant-based solar dryers. They point out that the FPC and ET have the highest thermal efficiency, while the solar tunnel dryers have the highest throughput capacity. The authors also discuss the potential applications of solar dryers in different industries, such as food processing and agriculture. The paper concludes that solar drying is a viable and sustainable method for drying products, and also provides a cost-effective and eco-friendly alternative to conventional methods.

Reference [115] presented a novel air-preheating technology, called the “Closed-ended Oscillating Heat-Pipe” (CEOHP) air-preheater, which was developed to increase energy efficiency in a dryer. The study found that the CEOHP preheater was able to reduce the energy consumption of the dryer by up to 40%, while still maintaining the same drying performance. Moreover, the CEOHP preheater has better reliability than conventional air heaters, as it was able to operate over a wide range of temperatures and humidity levels. Overall, the study concluded that the CEOHP preheater was an effective and reliable technology for improving the energy efficiency of dryers.

Tiwari et al. (2009) [116] investigated PV-T dryer behaviour. The system consists of a FPC, a forced air fan, a heater, and a drying chamber. The experiments conducted to determine the dryer performance in terms of temperature and relative humidity of the drying chamber and the efficiency of the system. In the drying chamber, 35–48 °C was the mean temperature, 15.5% was the mean thermal energy, 23.9% was the mean electrical exergy, and 25.1% was the mean thermal energy.

An efficiency of 19–25% was determined for the system, demonstrating that it effectively transferred solar energy to the drying chamber. As ambient temperature and humidity rose, the efficiency of the system decreased. This study has demonstrated that PV-T mixed mode dryers can be used to dry agricultural crops.

Fterich et al. (2018) [117] provided an experimental investigation of PV-T dryer. The dryer was tested to determine the effect of operating parameters such as solar radiation, ambient temperature, and air velocity on performance. The study results revealed that elevated radiation intensity, the higher the drying rate and the lower the drying time. The highest drying rate and drying efficiency were achieved at an air velocity of 0.5 m/s and 0.6 m/s, respectively. In addition, the ambient temperature was found to have substantial effects on the drying rate and the drying efficiency. The results also revealed that the dryer performance was very sensitive to the solar radiation intensity, and an increase of only 10 W/m^2 in solar radiation intensity led to an increase of 20% in drying rate and 19% in drying efficiency. It is worth mentioned that drying rate is “the proportion of heat energy used to vaporize moisture from food samples compared to the solar radiation that falls on the collector and the surface of the crop”, and drying efficiency is “the proportion of energy introduced into the air as it passes through the collector, relative to the amount of solar energy received by the collector”. This study provides a comprehensive understanding of the performance of the solar dryer and is useful for improving the design and operation of similar systems.

Tiwari et al. (2018) [118] studied the use of “Semi-transparent Photovoltaic Modules” (SPVMs) in a solar dryer to dry grapes. The study compared the drying performance of the SPVM integrated solar dryer with a conventional solar dryer, a mechanical convection dryer, and a solar tunnel dryer. The research showed that the SPVM integrated solar dryer worked the best, drying 0.033 kg/h. The mechanical convection dryer had a slightly lower rate of 0.024 kg/h and the solar tunnel dryer was the least efficient with a rate of 0.020 kg/h. It was also found that the SPVM dryer had the highest energy efficiency of 0.77, followed by the mechanical convection dryer and the solar tunnel dryer at 0.58 and 0.41, respectively. The study concluded that the SPVM integrated solar dryer was an effective way to dry grapes and could be used for other types of food products as well.

Tiwari et al. (2017) [119] examined the effectiveness of a PV-T air collector integrated greenhouse dryer (GH- PV-T-AD) as an efficient and cost-effective alternative to traditional drying systems. The study assesses the performance of the GH- PV-T-AD by examining the drying rate, temperature, relative humidity, and energy consumption of the system. Results show that the GH- PV-T-AD significantly reduces the drying time of agricultural products and increases the drying temperature, relative humidity, and energy efficiency. Compared to traditional solar dryers, the GH- PV-T-AD was also found to be more cost-effective. The study showed that the GH- PV-T-AD is a viable and cost-effective alternative to traditional drying systems, as it significantly reduces drying time, increases the drying temperature, relative humidity, and energy efficiency.

Fudholi et al. (2014) [120] presented behaviour analysis of solar drying system for red chili. The experiment was conducted in Malaysia. Results revealed that the drying rate increased as the air temperature and air velocity also increased. The maximum drying rate was found to be 0.068 $kg/m^2{\cdot}h$ and the corresponding air temperature and air velocity were found to be 35.3 °C and 0.25 m/s, respectively. The maximum efficiency of the system was found to be 32.8% and efficiency decreased as the drying rate increased. Red chili peppers in Malaysia can be dried using a solar drying process, based on the results of the study.

6. Conclusions

The current study revised the most important articles that studied methods to improve PV-T integrated greenhouse drying systems to make them self-sustainable, as these systems are usually required in areas where there is no connection to the electrical grid (rural and remote areas). These systems thermal modelling do not only assist in design, but also provides the option to choose the best possible dryer for the relevant climate. Several important studies on thermal modelling of a greenhouse desiccant in natural convection (passive) and forced convection (active) modes have already been performed. This study presented classification for passive and active systems used PV, thermal and PV-T systems, along with discussion. However, additional practical tests are needed to determine which PV-T technologies will be economically viable for solar drying processes. From the literature review, it has been noted that a significant portion of the heat energy is wasted during the drying process. This waste heat could have been used in other applications such as heating, which increases the efficiency of the system and makes it environmentally friendly.

Author statement

Dear Editors of Case Studies in Thermal Engineering,

I am pleased to submit our research article entitled "Photovoltaic-Thermal systems applications as dryer for agriculture sector: A Review" for consideration for publication in your esteemed journal.

This article reviews the applications of photovoltaic-thermal (PVT) systems as dryers in the agriculture sector. The paper presents a comprehensive analysis of the recent advancements in PVT systems, including their design, performance, and applications, for drying agricultural products. The article also explores the potential benefits of using PVT dryers over conventional drying methods, such as increased energy efficiency, reduced operating costs, and improved product quality.

As the lead author of this study, I confirm that the research was conducted in accordance with all ethical standards and procedures. We have no conflicts of interest to declare, and the research was not funded by any specific organization or individual.

We believe that this review article will be of great interest to your readership, as it highlights the potential of PVT systems in the agriculture sector, and provides valuable insights for researchers, policymakers, and practitioners working in the field. We thank you for considering our submission and look forward to hearing from you soon.

Sincerely,

Ahmed Al-Amiery.

Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

No data was used for the research described in the article.

Acknowledgment

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