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Integration of Active Solar Thermal Technologies in Greenhouses: A Mini Review

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Traditional agricultural greenhouses have been used to grow vegetables in the winter without any auxiliary heating. However, crop production is highly influenced by soil and air temperatures, humidity, and solar radiation. The aim of this paper is to review the recent active solar thermal technologies that help reduce the energy demand for greenhouse climate control and achieve intensive crop production. The review is categorized into the following topics: 1) locations for collector installation; 2) discussion on the different types of solar collectors, which include metal-based, glass-based, ceramic-based, plastic-based, and hybrid photovoltaic/thermal types for greenhouse applications; 3) heat release systems in active greenhouses in terms of basal heating, backwall heating, and air heating systems; and 4) short-term and long-term heat storage systems for greenhouses. Future studies on active solar greenhouses might focus on microclimate prediction, long-term heat storage, and system optimization.

Keywords: thermal collector, greenhouse construction, solar absorption, heat release, heat storage, crop growth

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INTRODUCTION

In recent years, the energy demand of civil building environmental control has been greatly reduced (Kelly et al., 2020), and substantial energy-saving potential still exists in other sectors, such as agricultural production buildings, because crop production directly accounts for approximately 10–12% of anthropogenic greenhouse gas emissions (Wu et al., 2020). Traditional solar greenhouses are passive solar systems with little human intervention in the heating process, where all heat transfer processes are self-regulated (Tong et al., 2018). However, active heating uses mechanical equipment and materials to change the heat transfer and capture process to improve crop production (Hassanien et al., 2016). To reduce the consumption of unsustainable energies, solar collectors have been applied to greenhouse projects.

The scope of this paper is to review the recent active solar thermal technologies that help reduce the energy demand for greenhouse climate control and achieve intensive crop production. Compared with related publications, this paper 1) introduces a new type of all-ceramic solar collector that can be used in greenhouse construction; 2) analyzes the four installation locations of solar collectors in greenhouse projects and proposes the inner surfaces of the backwalls; and 3) categorizes heat release systems in active solar greenhouses as basal heating systems, backwall heating systems, and air heating systems.

SOLAR COLLECTOR CATEGORIES

The most widely-used solar thermal collectors include flat-plate collectors, evacuated tube collectors, and compound parabolic concentrators (Gorjian et al., 2020a). This section mainly discusses solar

TABLE 1 | Comparison of different solar collector types.

Category	Form	Outlet fluid temperature	Thermal efficiency	Service life	Financial cost	Main references
Metal	Plate	Medium	65–80%	15–20 years	≈ $271/m^2$	(Attar et al., 2013; Yang et al., 2013; Akram et al., 2021)
Glass	Tube	Medium and high	20–89%	15–20 years	≈ $193/m^2$	(Kim et al., 2013; Chopra et al., 2020)
Ceramic	Plate	Medium	39–65%	>100 years	≈ $28/m^2$	(Zukowski and Woroniak, 2017; Ding, 2018)
Plastic	Plate	Medium	14–69%	No data	Less than metal, glass and PV/T collectors	(Jona and Rosso, 2008; Fabrizio, 2012)
PV/T	Plate/ tube	Medium and high	11–86%	≈20 years	≈ $818/m^2$	(Wu et al., 2019; Liang et al., 2021; Sohani et al., 2021)

collectors made of metal, glass, ceramic, and plastic in the form of plates or tubes. In addition, a photovoltaic/thermal (PV/T) Solar System is presented (**Table 1**).

Metal-Based Collectors

Metal-based collectors, usually in the form of flat plates, have dominated the market at temperatures ranging from 30°C to 80°C in greenhouses in the past decades due to their affordable investment and simple installation (Jeon et al., 2016). However, beyond this temperature range, the efficiency of the metal collector is relatively poor. In particular, at high altitudes, the metal plate collector tends to be damaged due to water freezing.

In addition to flat plates, metal plates used in greenhouses have various cross-sectional configurations to absorb more solar irradiation, such as corrugated, reverse-corrugated, trapeziform, and reverse-trapeziform plates (Ozgener and Hepbasli, 2005; Said et al., 2016). Previous studies have shown that corrugated plate collectors have an advantage over other forms in absorbing more solar radiation (Zheng et al., 2017).

The working medium flow inside or on the surface of the plate can be both liquid and air (Zheng et al., 2017). In addition, the service life of the metal collector is only 15–20 years owing to the deterioration of the absorptive coating on the surface of the plate (Yang et al., 2013).

Glass-Based Collectors

Among all solar collectors used in greenhouses at low-medium temperatures, the glass collector, normally in the form of an evacuated tube, is the most efficient (Chopra et al., 2018). The glass collector can generate heat over 100°C at a relatively low cost (Kim et al., 2013). In the past 20 years, due to the development of double glass vacuum tube production, its cost has been greatly reduced. As a result, the market for glass collectors has surpassed that of metal collectors (Teles et al., 2019). According to the market conditions in 2018, 77.8% of newly installed solar collectors were glass (Chopra et al., 2018). Although concentrating glass collectors or parabolic trough collectors can produce heat above 300°C, they are not commonly used in greenhouses (Kasaeian et al., 2017).

The structures of non-concentrating glass collectors are broadly classified into all-glass, heat-pipe, straight-flow (concentric cannula), and U-shaped tubes (Ramírez-Minguela et al., 2018). The glass tube consists of a selectively coated tube (the inner tube) inserted into another borosilicate tube (the outer tube). The vacuum is formed by the process of discharging air from the space between the inner and outer tubes. Vacuum tubes work efficiently because vacuum is a good insulator for heat dissipation (Papadimitratos et al., 2016).

Various types of glass collectors can be used in solar greenhouses for liquid heating, air heating, drying, and other applications. However, due to the destruction of the vacuum space and glass damage, the service life of glass tube collectors is as short as that of metal collectors, which hardly matches the life of a building (Yang et al., 2013).

Ceramic-Based Collectors

To solve the problems of conventional metal-flat and glass-tube solar collectors such as short service life and relatively high cost, scholars have devoted considerable efforts toward investigating long-life and low-cost solar thermal absorption materials that can be easily integrated into building construction, especially in developing countries. Therefore, a flat-plate collector made of vanadium-titanium black ceramic was invented and implemented (Ding et al., 2021). The ceramic coating has an absorption coefficient of 0.93–0.97, which barely decays with time (Żukowski et al., 2019). Moreover, this all-ceramic collector costs only $28/m^2 (Ding, 2018), approximately 1/20 of that of conventional collectors (Chopra et al., 2018). Compared with metal plate collectors, ceramic collectors have more abundant cross-sectional forms, such as corrugated, box-shaped, and tube-shaped plates.

Ceramic plate collectors are suitable for integrated installation; i.e., they have the potential to share the structure layer, the waterproof layer, and the insulation layer with the greenhouse in either the frame mode or the plie mode (**Figure 1**). These modes are appropriate for medium-to-large solar heating systems with limited investments.

Plastic-Based Collectors

In addition to the all-ceramic plate, another low-cost solar collector made of plastic was developed (Jona and Rosso, 2008). The collector is a 1 cm black hollow polypropylene plate. The collector consists of an absorber located between a 1 cm transparent hollow plate at the front and a 5 cm insulation

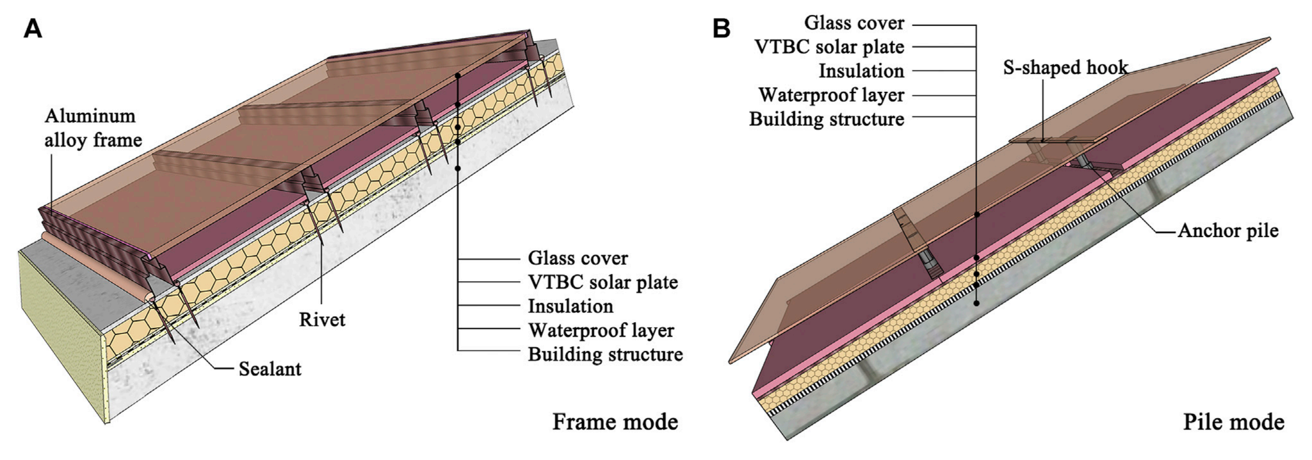

FIGURE 1 | Structural forms of the ceramic absorber integration pattern.

layer at the back. The tested efficiency of this collector is approximately 69% (Fabrizio, 2012).

PV/T Collectors

In addition to the above solar thermal collectors, PV/T collectors have good potential for solar greenhouses (Jouhara et al., 2016; Gorjian et al., 2021). Hybrid PV/T systems are combination of solar-thermal devices and solar-electric devices (Arefin, 2019). In these systems, the working medium [air (Tiwari and Tiwari, 2017) or liquid (Kirchner and Giovannetti, 2018)] extracts the excess generated heat from PV modules and improves the overall electric efficiency. Then, the extracted heat is used in low-to medium-temperature applications (Al-Waeli et al., 2017; Gorjian et al., 2020b). Researchers have performed numerical simulations and experimental testing regarding PV/T greenhouses (Vadiee and Yaghoubi, 2016; Singh et al., 2018). An experiment showed that under 1095 W/m^2 radiation the instantaneous efficiency of a PV/T greenhouse system is 32.2% (Wu et al., 2019).

INSTALLATION LOCATIONS OF SOLAR COLLECTORS IN GREENHOUSE PROJECTS

For solar collectors, four installation locations are normally used in greenhouse projects. First, solar collectors mounted on the south roof have better efficiency (Nayak and Tiwari, 2008). However, in this mode, the devices severely shade sunlight, which may lead to a reduction in agricultural production. To solve this problem, semitransparent PV/T collectors installed underneath greenhouse roofs can act as opaque envelopes (Zhi et al., 2018). Second, collectors installed on the north roof, or sometimes a small flat roof on the top, have a less negative influence on crops (Cossu et al., 2010; Yano et al., 2010). However, the system thermal performance is restricted because of poor orientation and relatively insufficient collector area. Third, placing collectors away from the greenhouse is a feasible way to capture sunlight for both solar devices and vegetables. However, compared with crop planting, such an installation may require larger land (Fabrizio, 2012). Solar collectors of the aforementioned three integration types are placed outside the greenhouses. The heat collected by the collectors must be transported into the greenhouse before heating the indoor air or soil, which may lead to thermal loss and material waste.

Collectors installed on the south surface of the backwall may solve the problems listed above. Moreover, this mode not only shares the transparent cover of the greenhouse with solar collectors but also elevates the thermal performance of the backwall. Therefore, in greenhouses with a solid backwall, such as quadrant-shaped (Wang et al., 2014) and chapel-shaped greenhouses (ELkhadraoui et al., 2015), solar collectors or absorbers can be installed on the inner surface of the wall.

HEAT RELEASE IN ACTIVE SOLAR GREENHOUSES

Heat release systems in active solar greenhouses mainly include basal heating, backwall heating, and air heating systems.

Basal Heating System

Basal heat distribution systems are usually hot water radiated along pipes (horizontal or vertical) throughout the greenhouse floor (Ghani et al., 2019). Heating systems placed under crops avoid the temperature stratification and Sun shading that occurs in a greenhouse and provide a moderate temperature (approximately 40°C). In the case of bottom heating, heat is transferred directly to the crop soil, and the root temperature should not exceed 25°C to avoid the risk of damaging the plant rhizosphere. However, these temperature ranges impose a heat output limitation on the radiant system, which cannot exceed 50–60 W/m^2 (ASHRAE, 2007).

Backwall Heating System

Backwall heating systems are usually associated with solar absorbers mounted on the backwall of the greenhouse (Lu et al., 2017; Esmaeli and Roshandel, 2020). These systems have two operation modes: "absorber radiation mode" (collecting loop only) and "absorber + basal radiation mode" (collection and heating loops).

The authors conducted a greenhouse project with a dual-mode heating system in the Tacheng Basin, China. In the absorber radiation mode, the floor heating loop is closed. The absorbers collect solar heat, convey most of the heat into the water tank, and release the remaining heat into the greenhouse by absorber radiation. The heat collected from the Sun circulates between the absorbers and the tank beneath the backwall to indirectly increase the indoor air temperature. In the floor radiation mode, both the collecting loop and heating loop are manipulated to heat the water in the tank and the soil in the greenhouse. The solar energy collected by the absorbers heats not only the indoor air but also the soil matrix through floor coils. This mode is controlled by both schedule and temperature. Via experimental testing, it was found that the system efficiency of the floor radiation mode is better than that of the absorber radiation mode.

Air Heating System

Air heating is another kind of heating system in active greenhouses. The air may flow over, under, or on both sides of an absorber. A flat-panel solar air collection system for greenhouse solar heating using phase change materials (PCMs) can be operated in both the single-pass mode and the charging-discharging mode (Benli and Durmuş, 2009). For the single-pass mode, air is drawn from the back end of the first collector through the back end of the second collector. For the charging-discharging mode, during the charging process, hot air from the air collectors circulates through the heat exchanger, and the heat is stored in the PCM. During the discharging process, the latent heat is released and the PCM solidifies.

HEAT STORAGE IN SOLAR GREENHOUSES

Solar thermal energy can be stored as sensible heat, latent heat, reaction heat, or a combination of the three (Gençer and Agrawal, 2018). Most agricultural applications are short-term (daily) storage (Zhou et al., 2017) that can handle only a small portion of the heat load and may not be sufficient during continuous overcast or rainy days. In contrast, long-term (seasonal) storage, which uses excess heat collected in summer to compensate for the heating shortages in winter, is an attractive option (Zhang et al., 2015).

Short-Term Heat Storage

In short-term heat storage systems, water, backwalls, and PCMs are used as storage media.

The most commonly used short-term heat storage medium is water. Researchers have developed a tank temperature model that predicts the water temperatures within the tank with an average accuracy of 0.4°C (Lu et al., 2017). Moreover, a general correlation between the water volume (V) and solar greenhouse area (A) was $V = 0.036A + 1.603$ ($R^2 = 0.7661$) (Sethi and Sharma, 2008). In addition to water storage tanks, plastic bags or ground pipes filled with water can be placed in solar greenhouses along the paths between crop lines, or water barrels along the backwalls. These simple devices can be used both as heat storage media and as solar collectors (Sethi and Sharma, 2007).

Backwalls also have the potential to store solar thermal energy. Researchers have developed passive backwalls with locally available inexpensive materials such as rammed-earth, gravel, aerocrete bricks, concrete hollow blocks, and hollow expandable polystyrene blocks in China (Zhang et al., 2020).

PCMs are generally only used as short-term storage media (Amirahmad et al., 2021) due to the lack of long-term stability (Zhou et al., 2012). PCMs are classified into organic, inorganic and eutectic types (Akeiber et al., 2016). Among these types, in organic ones are most applied in building constructions (Milián et al., 2017). PCMs typically convert the solid-liquid stage between 15 and 45°C and are suited for indirect gain systems in the range of 20–40°C (Rempel and Rempel, 2013). PCMs store 5–14 times more heat per unit volume than conventional storage materials and last longer (Ziapour and Hashtroudi, 2017). In terms of building application, PCMs are primarily used in thin components, such as PCM-impregnated gypsum boards, because a large heat capacity is available at a thickness of less than 2.5 cm (Kuznik et al., 2011). In addition, PCMs can be used as an alternative to low-volume water encapsulated in internal storage tanks, backwalls, thin tubes or pouches (Pasupathy et al., 2008). The heat absorption and transfer mode of thin PCM walls is suited for solar greenhouses that need stable heating at night (Rempel and Rempel, 2013).

Long-Term Heat Storage

Long-term or seasonal energy storage is an effective solution to overcome the natural imbalance between supply and demand periods (Wang et al., 2017). This subsection mainly summarizes the following three long-term heat storage systems: the ground source heat pump (GSHP) system, the rock-bed heat storage system, and the soil heat storage system.

First, most seasonal heat storage systems use heat pump systems as their heating sources. Research has proved that the GSHP systems used in solar greenhouses have advantages over conventional systems (Noorollahi et al., 2016). However, the relatively high cost of GSHP systems, especially heat pumps, has prevented the system from being widely used in agricultural production, especially in developing countries. Although improved systems such as PV/GSHP and PCM/GSHP have been invented (Anifantis et al., 2017) to make GSHP environmentally friendly and energy efficient, their initial costs are even higher.

Second, to address the energy imbalance and high cost, some scientists filled two excavated canals in the greenhouse with rocks to increase its heat storage (Jain, 2005). The results showed that the nighttime indoor air temperature in the rock-bed greenhouse increased by approximately 10°C compared with the reference greenhouse (Kürklü et al., 2003). The data collected indicate that the most commonly used rock-bed material is gravel with diameters of 20–100 mm. The empirical relationship between the total heat capacity of the rocks used (C_r) and the solar greenhouse area (A) is $C_r = 46.375A + 14{,}483$ ($R^2 = 0.8731$) (Sethi and Sharma, 2008).

Third, in recent years, soil borehole heat storage technology has been introduced into greenhouse heating (Xu et al., 2014). Unlike traditional underground heating systems, the system does not require a heat pump. Therefore, the cost is greatly reduced. The experimental results showed that the system energy loss and the soil heat loss accounted for 48.0 and 7.3% of the total energy collected by the solar collectors, respectively. Soil heat loss is not cross-seasonal storage loss, but summer loss. The underground soil temperature remained high for longer. Therefore, the seasonal heat energy storage system was feasible (Zhang et al., 2015).

DISCUSSION

This paper reviews the energy performance of some recent solar thermal technologies that have helped reduce the fossil energy demand for greenhouse microclimatic control to enable intensive crop production. First, solar collector materials include metal, glass, ceramic, and plastic. Among these collectors, ceramic-based collectors have the lowest investment cost and the longest service life, while glass-based collectors usually have the highest efficiency. In greenhouses with a solid backwall, solar collectors are installed on the inner surface of the north wall to ensure the best efficiency. Second, heat release systems in active solar greenhouses mainly include basal heating, backwall heating, and air heating systems. A combination system may be adopted according to the plant requirements. Third, most agricultural applications are short-term storage, while long-term storage is an attractive option.

Future studies on active solar greenhouses may focus on the aspects of microclimate prediction, long-term heat storage, and system optimization: 1) the microclimate prediction at unsampled points within greenhouses according to theoretical models, including not only air and soil temperatures but also humidity, ventilation, irradiation, CO_2 concentration, and lightning; 2) the model of latent heat storage efficiency for greenhouse heating, especially that of the borehole thermal energy storage, aquifer thermal energy storage and new PCMs; and 3) the cost-benefit analytical tool to determine the optimal configuration of a heat storage-release system, such as weighing additional devices cost versus yield increase at higher indoor temperatures.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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