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A Review of Greenhouse Technology and its Integration with Photovoltaic Cells

Manju Bhardwaj[1] and Shikha Singh*[2]

[1-2] Faculty of Electrical and Electronics Engineering, Shri Ramswaroop Memorial University, Barabanki - 225 003, Uttar Pradesh, India

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Abstract

Greenhouse technology is one of the prominent solutions for agricultural cultivation where harsh climatic conditions occur. Extreme summer/winter temperature is a major setback for crop production in greenhouse environment throughout year. Selection of shape and material of greenhouse is a critical parameter for the optimal growth. Agricultural products dried in greenhouse have been proven to be of higher quality than those dried in open sun because they are shielded from dust, rain, insects, birds, and animals. An exhaustive literature review reveals that even-span roof and Quonset shape greenhouses are widely used for growing and drying of the crop. To make self-sustaining greenhouse system, photovoltaic (PV) modules are added onto the roof of the greenhouse which can provide electrical energy as well as crop production with higher efficiency. A detailed review of the construction materials of PV cell has been carried out. In this paper, an attempt has been made to critically review of various shapes and sizes of greenhouse structure to select optimal one for a specific extreme condition.

***Key words*:** Greenhouse shapes, Solar energy, Agriculture products, Photovoltaic cell, GiSPVT

It is a well-known fact that food is one of the basic requirements of any individual on the earth. In India, around 70% of the total population resides in the rural areas and the major source of income to fulfill their basic needs is from agriculture and aquaculture sector [1]. Therefore, it becomes important for the economic growth of the country. However, due to rapid modernization, the cultivated land is being converted for commercial purposes such as for buildings, express ways etc. which results in shortage of the agriculture land. This leads to scarcity of food and other requirements. Moreover, changes in the climatic conditions such as global warming affect the food production and therefore it becomes a great concern for quality production. The major factors for climate change include increased use of fossil fuels, deforestations and degradation of forest that produces greenhouse gases (GHG). GHG such as CO_2, CH_4, N_2O and fluorinated gases affects the human being in a very severe way. Fish production also get affected by the climate changes directly and/or indirectly [2].

To increase the agriculture and aquacultural production and to address these issues in technological advanced environment, agriculture sector requires modern techniques at various stages. Greenhouse is widely adopted in farming and fish production and have an important implication on agro-ecosystems, society as well as on economy. It is used to protect crops and fisheries (aquaculture) from extreme climatic conditions, pests and diseases. Furthermore, it offers the advantage of increased output during the off-season, meeting the huge retail chains throughout the year for fresh and high-quality products [3]. Generally, it is used for farming of crops (Tomato, eggplant, pepper, zucchini, melon, squash, lettuce, cucumber etc.) along with some flowers, fishes, ornamentals, and fruits (primarily strawberries) [4]. It can be used to increase the annual yield of aquatic animals. Selection of greenhouse mainly depends on various factors such as geographical location, climatic zones, budget, cultured species and production system. The inner conditions of the greenhouse such as temperature, humidity, sunlight can be controlled and it is possible to prolong the season of cultivation. High amount of energy is required for various operations such as heating, pumping, cooling, ventilation, drying, and artificial lighting. Therefore, photovoltaic (PV) cells may be integrated onto the roof or onto the walls of the greenhouse to generate electrical power, thereby making it self-sustainable [1-5].

Various structures of green house, green house integrated with solar panels and greenhouse integrated solar photovoltaic thermal (PVT) system has been reported in literature [6]. The installation of semi-transparent PV modules on a greenhouse roof or wall surface can be beneficial when aquaculture require moderate shading under high-irradiation conditions [7-8]. PVT system combines the benefit of solar PV and solar thermal technologies within a greenhouse structure. These are hybrid system and generate both electrical energy and thermal energy using solar radiation ensuring self-sustainability. It incorporates PV panels, which consist of solar cells to convert solar radiation into electricity. Excess electrical energy can be stored in the energy storing devices for later use or feed back into the grid. Alongside PV panels, solar thermal collectors can also be integrated into greenhouse to capture solar radiation for thermal energy. Thermal energy can be

***Correspondence to:** Shikha Singh, E-mail: Ishikha.singh@gmail.com; Tel: +91 8574680415

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utilized for various purposes within the greenhouse such as space heating, water heating or powering absorption chillers for cooling. The thermal energy can be stored in thermal storage system and used during low solar radiation for maintaining optimal temperature in greenhouse or for other applications. This arrangement offers efficient electricity generation while simultaneously providing valuable thermal energy for heating, cooling and other applications within the greenhouse. This promotes energy self-sufficiency, reduces reliance on conventional energy sources and enhances the overall sustainability and productivity of greenhouse. The performance of GiSPVT is further enhanced using Earth Air Heat Exchanger which is the method of cooling and heating of any closed space using thermal energy of earth [9]. A comprehensive survey on various greenhouse shapes for different climatic zones, crops and fishes are reported in literature [10].

This paper deals with the exhaustive review of such existing system to select one for a particular operation. The paper is categorized in five sections. Starting with Section I, the others sections cover the classification and shapes of greenhouse, literature review on classification and fabrication of PV Cells, comparative features based on efficiency and others options for further enhancement, latest trends and future developments in greenhouse technology.

Classification and shapes of greenhouse

The structure of greenhouse depends on various factors such as climatic zones, applications, cost, type of material, availability etc. Generally, frames of inflated structure covered with a transparent material are used in which crops are grown under controlled environment. Controlled environment cultivation have been evolved to create favorable micro-climates, which favors the crop production throughout the year or when required [11]. These are also associated with the off-season production of ornamentals and foods of high value in cold/warm climate areas where outdoor production is not possible. The primary environmental parameter is temperature, usually providing heat to overcome extreme cold conditions and/or vice versa. However, environmental control also includes controlled light either by shading or adding supplemental light, carbon dioxide levels, relative humidity, water, plant nutrients and pest control [12-13]. The classification of greenhouse based on different parameters is shown in (Fig 1).

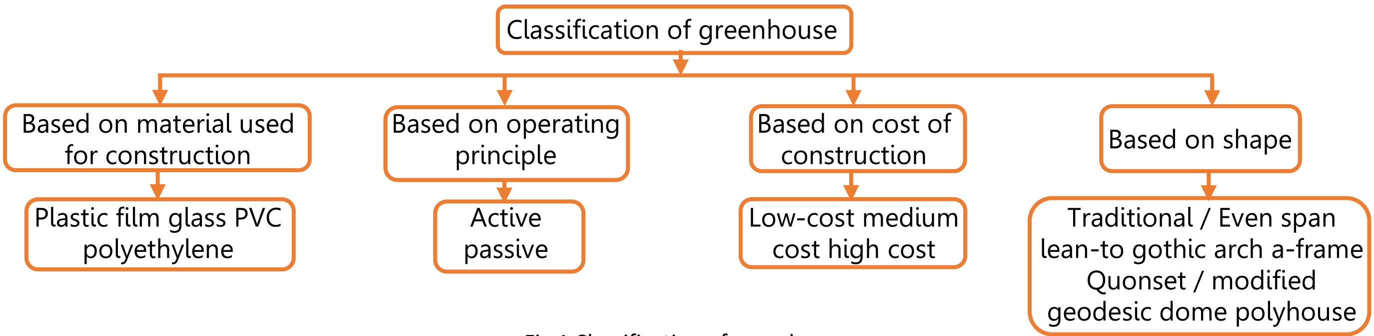

Fig 1 Classification of greenhouse

A. *Classification based on material used for construction*

Materials used in the construction of greenhouse is an important parameter because this has direct influence on the air temperature. The choice of materials used in the construction of a greenhouse is a crucial factor that directly influences the internal air temperature and overall performance of the greenhouse. The types of frames and method of fixing also varies with covering material like glass, polyethylene film, acrylic, polycarbonate etc. Although there is an advantage in each type for a particular application, in general there is no single type greenhouse, which can be considered as the best [14].

B. *Classification based on operating principle*

Two types of agricultural greenhouses can be categorized based on working principles which utilize solar energy for heating purposes. Passive greenhouses use collectors and designed for maximizing the solar heat gains by using a special cover and structure materials while the active greenhouses, equipped with solar systems, utilizes a separate collecting system from greenhouse. Passive greenhouses rely on design and materials to harness solar energy directly, whereas active greenhouses employ external solar collection systems to manage and distribute solar energy more dynamically. It incorporates an independent heat storage system, such as adding thermal energy inside the greenhouse from an air heating system in addition to direct thermal heating. In case, both heating and cooling are needed, greenhouse provides a combination of passive and active techniques whenever required [15]. The active heating methods by using solar collectors saves the electrical energy but no system is incorporated to reduce the losses occurs in the surroundings. There are passive methods available but efficiency of those system is low [16-17].

C. *Classification based on the cost of construction*

Greenhouses are a technology-based investment. The high level of technology ensures the better results but it increases the cost of construction and complexity of the system. Three categories of greenhouse based on cost of construction have been defined for selecting the most appropriate investment as per their needs and budget. Low level greenhouses result in a suboptimal growing environment which restricts yielding of crops and provides less protection from pests and diseases. Medium level greenhouses offer a compromise between cost and productivity. It is more economical. High level greenhouses are having specific qualities as optimum ventilation, best utilization of space, maximum heat conservation or allow better light penetration etc. but they are costly [18].

D. *Classification based on shapes*

There are advantages in each shape for a particular application. Different shapes of greenhouses are designed to meet the specific needs. The choice of greenhouse depends on factors such as available space, climate, budget, intended use, and personal preferences of the grower [14-18].

Traditional / even-span greenhouse: This is the most basic and commonly used greenhouse as shown in (Fig 2a-b). It has a rectangular or square shape with straight sidewalls and a peaked roof. The even-span design allows for efficient use of space and easy installation of equipment. This is suitable for crop production and is often used in commercial agriculture [15].

Lean-to greenhouse: A lean-to greenhouse is built against an existing structure, such as a house or a wall. It shares one wall with the existing structure and has a sloping roof as shown in (Fig 2c). Lean-to greenhouses are cost-effective and space-saving options, ideal for homeowners with limited yard space [16].

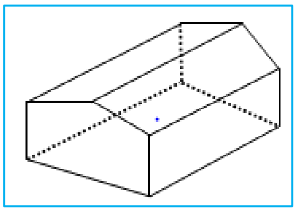

Fig 2a Even span

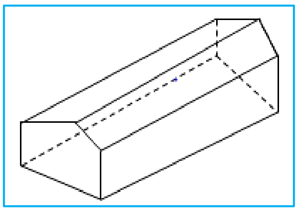

Fig 2b Grabic uneven span

Gothic arch greenhouse: This type of greenhouse features a curved or gothic arch-shaped roof as shown in (Fig 2d), which provides added strength effectively. The curved design allows for better air circulation and maximizes sunlight penetration. Gothic arch greenhouses are popular in regions with heavy snowfall or windy conditions [17].

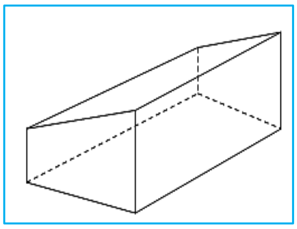

Fig 2c Single slope

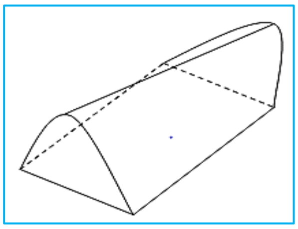

Fig 2d Gothic arc

A-Frame freenhouse: A-frame greenhouse resembles the letter "A" in its structure. A-frame greenhouses are compact, provide good headroom, and are suitable for smaller spaces or hobbyist gardeners [17].

Quonset hut greenhouse: Quonset hut greenhouses as shown in (Fig 2e-f) have a semi-circular or hoop-shaped design. They are made from metal or PVC pipes covered with a plastic film or greenhouse polycarbonate. Quonset hut greenhouses are easy to construct, cost-effective and offer good strength against wind and snow loads and often used in commercial operations [17].

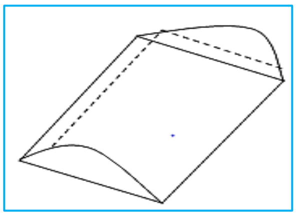

Fig 2e Quonset

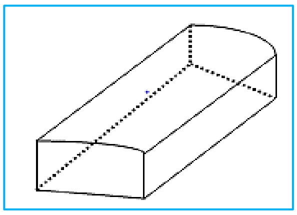

Fig 2f Modified quonset

Geodesic dome greenhouse: Geodesic dome greenhouses as shown in (Fig 2g) have a spherical or dome-shaped structure composed of interconnected triangular panels. The dome shape provides excellent strength and stability, making it suitable for extreme weather conditions. It offers efficient use of space, good airflow and even light distribution.

Polyhouse greenhouse: A polyhouse, also known as a polytunnel or hoop house as shown in (Fig 2h), is a low-cost greenhouse made with a series of hoops covered with a plastic film. Polyhouses are popular among small-scale farmers and gardeners. They offer protection from the elements and extend the growing season while being relatively easy to set up and maintain.

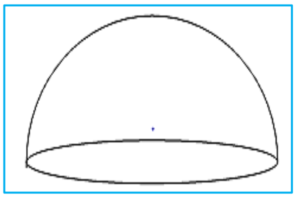

Fig 2g Spherical dome

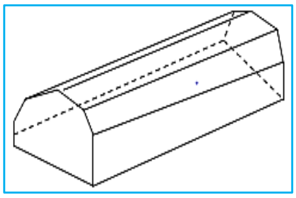

Fig 2h Tunnel greenhouse

Photovoltaic thermal (PVT) cells

Due to rapid population expansion and economic development, alternative energy sources are gradually being absorbed into the future global energy mix [19-20]. Different solar based technologies are widely used and acknowledged as clean and emitting low greenhouse gases, aiding in the efforts to mitigate climate change [21-22]. Solar energy is radiant energy that can be captured by a variety of cutting-edge technologies, including building-integrated photovoltaic (BIPV), solar thermal energy, solar heating, solar architecture, and artificial photosynthesis [23]. One of the promising solutions to the exponential rise in food and energy demand is greenhouse technology combined with photovoltaic thermal (PVT). Photovoltaic become most advanced and evolving technology for generating electrical energy [23-24]. PV materials including monocrystalline silicon, polycrystalline silicon, and amorphous silicon convert solar radiation into electricity [22-24]. These combined land and food issues may seem insurmountable, but with the help of aqua-voltaics (dual use of water for solar photovoltaics and aquaculture), agri-voltaics (dual use of land for solar photovoltaics and agriculture), intelligent and cross-disciplinary approaches, can be greatly strengthened [25]. In recent years, numerous scientists have worked on these issues of greenhouse heating using both active [26] and passive methods [27-28].

Passive systems are used to minimize the heat loss and maximize the solar thermal gain. Significant efforts have been contributed by researchers in the field of passive heating of ponds water. In [29], pond water with transparent plastic sheet is covered to increase the water temperature and cut down the heat loss. Transparent plastic covers made of polyvinylchloride (PVC) with air bubbles were used to reduce the heat loss effectively and increase the pond temperature [30]. Researcher has studied the effect of greenhouse on an aquaculture pond heating with the help of thermal modeling. The fishpond with greenhouse system can provide the favorable water temperature from 16 °C-35 °C against 5 °C-15 °C temperature of ambient air for prawn fish farming during the winter season. The parametric studies revealed that 1 m depth of water with 0.25 m depth of freeboard is enough to get optimum water temperature. The thermal efficiency of the fishpond–greenhouse system can be obtained as 19.1%. Practicability of the greenhouse used for aquaculture pond heating is very encouraging for prawn farming in cold region of northern. In active heating system, thermal energy extracted from different renewable energy sources are used to heat pond water. Invention of solar collectors and development of high efficiency solar collectors has led to the active heating of pond water in harsh climatic conditions. In this technique, solar energy harnessed by flat plate collectors (FPC)/ evacuated tube collectors (ETC)/ Photovoltaic thermal collectors (PVT) are used to heat the pond water in winter. Active heating of pondwater using different solar collectors system has been studied [31]. Bataineh has studied and developed a transient analytical model for evacuated tube collector assisted indoor swimming pond [32]. In [33], numerical study of different swimming pond heating methods for energy saving were carried out, their result demonstrated that evacuated tube collector performed better than flat plate collector, and provide 22.5% total heating requirement for the area equal to the pond surface area for the simulation period [33]. In [34], the comparative study of swimming pond heating and found that system the solar blankets (pond covers) and solar collectors can effectively increase the pond water temperature. In [34], it was concluded as combination of both (active and passive method) can be used to increase the pond temperature significantly.

A. *Classification of photovoltaic (PV) cell*

Photovoltaic (PV) cells are the emerging technology which are used to generate electricity from solar radiation. The construction materials used for designing of PV cells are silicon, polysilicon amorphous silicon and nano materials. (Fig 3) depicts the classification of PV cell. Various crystalline solar cell modules constructed by using mono crystalline, polycrystalline, and ribbon materials are reviewed in this section [35-36].

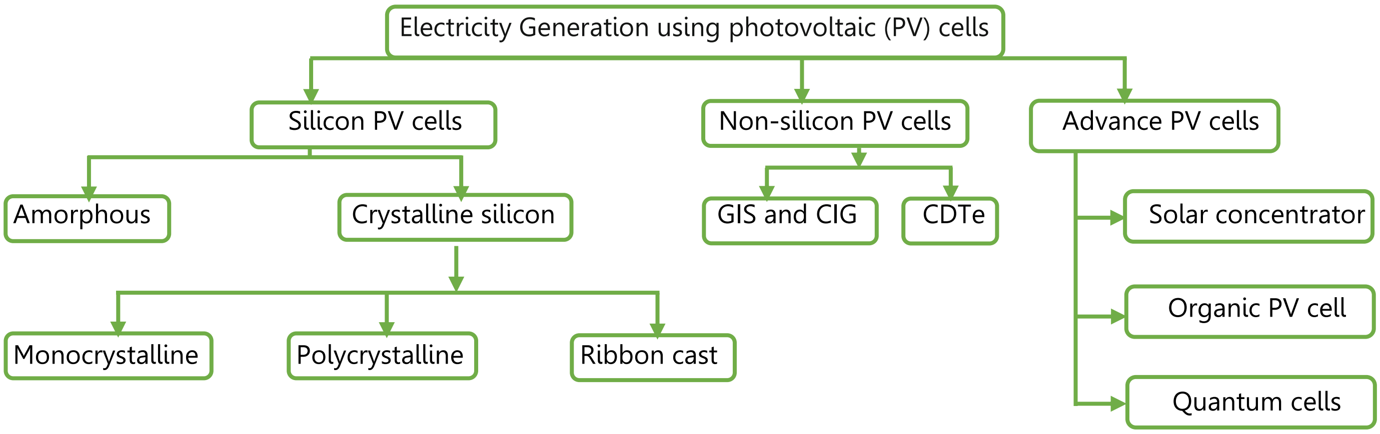

Fig 3 Technology based classification of PV solar cells

B. *Recent development in PV cell*

Tripathy *et al*. [37], Yoo and Manz [38], and Green *et al*. [39] have shown the photovoltaic (PV) cells structures such as crystalline silicon wafer-based cells (c-Si) and thin films such as amorphous (a-Si), organic PV (OPV), Dye-sensitized solar cell (DSSCs), and Copper Indium Gallium Selenide (CIGS). Monocrystalline and polycrystalline based solar panels are the most effective panels widely used in the market as it provides the higher efficiency rating as 26% compared to the other solar panels whose efficiency lies between 11% and 17% [36-39].

Various PV cells including crystalline silicon PV, thin-film PV cells, and third generation technologies (OPV and DSSCs), were surveyed by Lee and Ebong [40]. The research outlined the benefits of crystalline silicon photovoltaics (PV) as its production and availability is very easy and it's very cheaper compared to other latest technologies [40]. Monocrystalline Si silicon photovoltaics (PV) cells are developed by integrating crystals of pure silicon which are cylindrical in shape [24]. Monocrystalline Si PV cells were designed by melting pure silicon and doping of n-type and p-type semiconductors using melting process. Monocrystalline Si silicon photovoltaics (PV) cells are chemically stable with efficiency of 11-16% and can be used for a very long time [42-43].

In multijunction solar cells, many materials are used for construction with different band gaps throughout the solar spectrum and provide the maximum efficiency of 18-20%. According to [45-46], PV solar is made by using single-junction solar cells that have been stacked on top of each other so that each layer has a smaller band gap than the one before it. As a result, it absorbs and converts the energy of the photons as greater than the band gap of the lower layer and less than the band gap of the higher layer [47]. The polycrystalline cells are made in a square-shaped tank from pure molten silicon. The crucial stage of polycrystalline cells is cooling process for determining the grain size and distribution of impurities. The structure of polycrystalline cells is less perfect than mono crystalline Si, which causes an efficiency loss of 1% [48-49]. Due to a lack of higher energy photon absorption, polycrystalline cells are blue in color. Due to many advantages as they are inexpensive, have a longer lifespan, reliable and do not degrade over time but are easily impacted by temperature, they are primarily employed in sub-Saharan nations [45-47]. Non-crystalline PV cells were reported by Oulmi *et al*. [50]. These silicon chips are of the second generation and are non-crystalline, making them newer than mono- and polycrystalline cells. The PV modules efficiency at standard Test Conditions (STC) is shown in the (Table 1) [36-56].

Table 1 Efficiency of PV panels based on construction material

PV panels (Based on construction material)	Efficiency of PV panels at STC (%)	Reference
Cadmium telluride (CdTe)	9% - 22.1%	
Polycrystalline Silicon (Po-C-Si)	11% - 22.3%	
Amorphous Silicon (a-Si)	5% - 11.9%	
Monocrystalline Silicon (mo-C-Si)	15% - 26%	
Copper Indium Gallium Selenide (CIGS)	10% - 19.2%	[36-56]
Heterojunction (HIT)	18% - 20%	
Organic photovoltaic (OPV)	4% - 11.2%	
Dye-sensitized solar cell (DSSC)	2.9% - 11.9%	
Micromorph silicon (μC-Si)	8% - 10 %	

Conclusive observation of literature review

Solar photovoltaics (PV) modules convert solar radiation into electricity with 15% to 18% efficiency. A large portion of the received solar radiation is dissipated as heat during this process, which raises the surface temperature of the photovoltaics (PV) module and results in a significant reduction in electricity output. A hybrid PVT module has the benefit of both generating electricity and acting as a thermal collector. The cooling medium (usually air/water) extracts the excess generated heat from the photovoltaics (PV) module in this hybrid collector, improving overall electric efficiency [10]. The heat extracted can be used in low- to moderate-temperature applications. The electricity generated by the photovoltaics (PV) modules is consumed by electric facilities, with the excess stored in batteries in greenhouse integrated PVTs, while the produced heat is used to provide an appropriate indoor environment for the greenhouse, making the entire system self-sustaining. Green house integrated semi-transparent photovoltaic cell is a self-sustainable system used for crop production, crop drying and providing electrical energy for operation. For obtaining an efficient performance of GiSPVT, the selection of suitable greenhouse structure as shapes, its orientation, construction material based on working principle are in great importance [11-65].

Table 2 Greenhouse shapes and its applications

Greenhouse design	Observation	Applications and seasons	Reference
Quonset, Modified Quonset, Pyramid, Tropical, Parabolic shapes	The solar greenhouse dryer was designed in Quonset shape with two different materials. Quonset is capable of providing 64% of rise in temperature in comparison to atmosphere temperature, tropical and pyramid greenhouse design provides 57% of rise in temperature, parabola and Quonset greenhouse design provides 55% of rise in temperature and igloo greenhouse design provides 53% of rise in temperature during summer season.	• Agriculture crop drying (pepper and tomatoes) • Summer	[64]
Geodesic dome	The thermal analysis of a geodesic dome type solar dehydrator is carried out and observed as the moisture content is reduce to 15% from 89.5% in 20 days in the month of august.	• Agricultural products (chilli, capsicum) • Winter	[65]
Geodesic dome	Solar fruit dryer in shape of geodesic dome using bamboo and wood is designed and experimented as it gives an average rise of temperature of 40°F during the summer season and 16°F temperature rise.	• Agricultural product (grapes) • Winter, Summer	[66]
Uneven Span modified arch Greenhouse integrated semi-transparent PVT	Uneven span arch based GiSPVT system is designed with aqua pond for aquaculture. The greenhouse temperature shows the temperature of 5°C with respect to ambient temperature for Northern India region.	• Aquaculture (fish) • Winter	[25]
Parabolic roof structure made from poly cage net, nylon net and polyethylene roof structure.	The experimental analysis is carried out in the Northern part of Thailand where the air temperature difference is 15˚C-20˚ between day and night. The 3 types of cages are designed as normal fish cage, green house fish cage and greenhouse fish cage designed with plastic film which provides heat loss reduction. The experimental study results conveyed that greenhouse cages through insulation (plastic) film fish cage shows the rise in growth rate of fish for farmers.	• Aquaculture (fish) • Winter	[14]
Insulated north wall type, Arch Type, Tunnel type	Experimental analysis is carried out for an application of drying the resin coated Mable for Udaipur, Rajasthan India climatic conditions. Three types of greenhouse dryers are designed (North wall insulated type, solar tunnel and Arch type) using micro polyethylene sheets. It is observed as tunnel type greenhouse solar dryer provided the promising results by raising the resin coated marble temperature above 45°C and maintaining below 60 °C.	• Resin drying • Summer	[62]
Even-span, modified arch and Quonset types	The Quonset greenhouse shown the best performance in capturing solar than even-span and modified arch types in northern areas of Iran.	• Fruits, Vegetables • Summer	[63]
Even-span, uneven-span and elliptic types	Uneven-span shape greenhouse received the maximum solar radiation followed by the even-span and elliptical shape after experimental analysis. Also, east–west orientation is appropriate configuration for drying applications as it receives maximum solar radiation in winter.	• Crops drying • Winter	[12]
Un-even Greenhouse-integrated semi-transparent photo-voltaic thermal (GiSPVT)	Experimental analysis concluded as an overall exergy decreases by increasing of packing factor using Greenhouse integrated semi-transparent photo-voltaic thermal (GiSPVT).	• Aquaculture • Winter	[5]

Potential future trends for greenhouses and its integration with pvt

Future greenhouses are expected to prioritize energy efficiency through advanced insulation, smart climate control systems with integration of renewable energy. Advanced Climate Control system optimizes temperature, humidity, CO_2 levels, and ventilation. Vertical farming is latest technology involves growing crops in stacked layers using artificial lighting and controlled environment ensuring maximized land use and increased crop production per unit area. This also reduces water usage, minimizes transportation distances, and offers opportunities for urban agriculture.

Artificial intelligence and machine learning algorithms may be incorporated to analyze real-time data and make adjustments to create the ideal growing conditions for various crops, maximizing yields. Latest techniques such as drip irrigation, hydroponics, and aqua phonics may be widely used to reduce water consumption while maintaining optimal plant growth. Various sensors, IoT devices, and data analytics to monitor plant health, environmental conditions, and crop growth may be used. This Real-time data collection and analysis will enable growers to optimize resource allocation and address issues promptly, improving overall productivity. Various sustainable and recyclable materials such as Bio-based materials, recycled plastics, and renewable resources will be favored over traditional to reduce environmental impact. These trends indicate a shift toward more sustainable, efficient, and technology-driven greenhouse farming practices. The future of greenhouses lies in leveraging innovation and data-driven approaches to optimize resource utilization, minimize environmental impact, and increase food production in a controlled and sustainable manner.

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