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Integration of solar technology to modern greenhouse in China: Current status, challenges and prospect

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ABSTRACT

Given the threat of environmental degradation and land deterioration to conventional agriculture, modern greenhouse cultivation has attracted increasing attention as an effective alternative. However, the high energy consumption of greenhouse systems is concerning given the need to limit the environmental impact of human activities. The solar integration to agricultural greenhouse in the form of modern solar greenhouse has the potential to simultaneously respond to the declining availability of suitable land and the imperative for minimum emissions. In this review, an overview of China's progress towards the development of modern solar greenhouses, as well as the attempts to mitigate the effects of heat loss, shadowing, and poor light condition is presented. A promising prospect is shown by China's modern solar greenhouses at present levels of performances and costs exemplified by the photovoltaic (PV) greenhouses with a practicable payback period of less than 9 years. Additionally, application of advanced solar technology for better thermal storage, PV power generating and light utilization balance has been proved effective to further promote solar energy utilization in modern solar greenhouses.

1. Introduction

Conventional open field farming has traditionally dominated agricultural production, despite its variable output as a consequence of inclement weather patterns and limitations of suitable geographic or climatic zones. In recent years, the problems of climate change and environmental destruction caused by human activities, urbanization, desertification, deforestation, and salinization, have further aggravated the issue of agricultural productivity and food security [1]. The emerging protected cultivation in greenhouse opens a new perspective in current modern agricultural sector by carrying out of water-saving, economical land use, and effective production advantages even in harsh circumstances [2,3]. Countries in the world such as Netherland, Israel, Japan, etc. are taking a proactive approach towards developing advanced facilities equipped greenhouses, which shall allow the adaption of outer microclimate closer to the optimal growth condition of plants by controlling parameters like the temperature [4], relative humidity [5], light [6], and carbon dioxide concentration [7].

Meanwhile, energy delivery is a critical input to the effective operation of modern greenhouses. In a literature survey of greenhouses in different countries by Hassanien et al. [8], the annual electrical energy consumption per unit greenhouse area is among 0.1–528 $kW\,h\,m^{-2}\,yr^{-1}$. And the cost of a greenhouse in Turkey heated by coal is calculated by Canakci et al. [9], the total annual cost per ha could be as high as 65,891.5–151,220.6 $/year. Such energy-intensive consumption brings about challenges with the expansion of the greenhouse scale, and also gives rise to the wide concern of the environmental impact. Since the overwhelming majority of modern greenhouses rely on burning fossil fuels and/or using electricity, and conventional energy combustion has been regarded as the primary contributor to the greenhouse gas emission as revealed by [10,11] that 90% of the CO_2 emission originates from the fossil fuels, it shall greatly contribute to the global warming and the environment degradation. Additionally, electricity transferring to greenhouses located within remote areas is yet another problem to be addressed. Therefore, there is an urgent need to seek renewable energy source for the sustainable

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development of modern greenhouses.

As a most populous nation with the largest greenhouse farming worldwide [12], China has made great efforts to develop large-scale modern greenhouses whilst seeking for more sustainable energy exploiting methods. The solar integration to agricultural greenhouse in the form of modern solar greenhouse is implemented as an important project by the Chinese government. Up to now, extensive policies to realize modern solar greenhouse development have been released [13–15], and great achievements have been achieved in the field of engineering. This paper aims to present a better understanding of China's progress towards the development of modern solar greenhouses based on exploration of solar integration status, challenges and prospects on advanced solar technology application. First, a comprehensive overview is given over the development status of modern greenhouses and solar industry in China, and the scenario of solar integration is analyzed from the perspectives of green energy supply and PV's growth strategy. Second, application cases of modern solar greenhouses in China, including PV greenhouses and solar thermal greenhouses (integrated with solar collectors) as well as the economic benefits and challenges are investigated. Third, advanced solar technologies for applicable modern greenhouse integration from researches are reviewed to provide an insight into the integration prospect. This paper will not only benefit the China's insiders by providing systematic information for policy and technology guidance, but also be valuable to present the case in China for other countries' reference.

2. Overview of China's modern greenhouse, solar industry development, and their integrated scenario

According to the National Agricultural Mechanization Statistics 2013, the total amount of greenhouse cultivation in China has approached to 2,000,000 ha [16], far exceeding any country on a global scale. Along with its extension in planting scale, the greenhouse types also experienced evolutions from the initial small shed to low tunnel, then to much larger architectures such as the plastic tunnel, solar greenhouse and multi-span greenhouse, which dominate the up-to-date forms of modern greenhouse in China [17]. Fig. 1 shows the areas of the three modern greenhouse types during 2009–2013. The total area of modern greenhouses has undergone a significant increment as indicated that the average annual growth rate nearly amounted to 20.8%. Specifically, solar greenhouse plus multi-span greenhouse shows a prominent expansion regarding their yearly proportion to the total amount, which shall make a great contribution to the advancement in modern greenhouse cultivation.

Given the rapid progress towards the development of China's modern greenhouses, rising concerns over their high consumption arise as a consequence of the massive requirements for energy-intensive environmental control facilities. Table 1 has a collection of the annual energy requirement per unit greenhouse area with different loads in China. It is indicated that the variation of the energy load leads to an energy consumption ranging from 5.4 to 847.4 MJ m^{-2} yr^{-1}. For multi-greenhouse in northern part of China, the annual coal burning for heating per ha to keep a relatively warm condition for plant growth is estimated to be 1499–2998 t. In the southern regions, the electricity consumed for summer cooling and ventilation could be as high as 300 MW h ha^{-2} yr^{-1} [18]. These suggest the necessity of generating electricity or thermal energy for greenhouse supply. Under the dual pressure of the depletion of fossil fuel reserves and reduction of emissions to minimize the adverse environmental impact, society is moving towards seeking more sustainable energy supply methods.

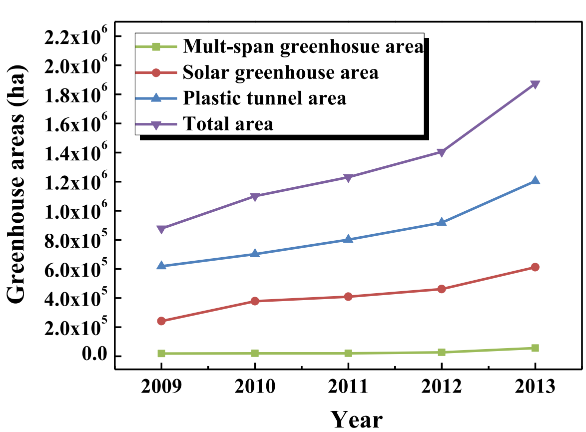

Fig. 1. Greenhouse areas in China from 2009 to 2013. *Data source*: The National Agricultural Mechanization Statistical Yearbook (2009–2013).

Solar power utilization turns into one of the most promising ways to handle the challenges of energy demand problems due to its clean and inexhaustible nature. In China, solar industry has also maintained a rapid pace of development. The manufactured PV modules have achieved an exponential growth from less than 4.382–36 GW in just the past six years. An illustration of the manufactured PV modules in China from 2009 to 2014 is shown in Fig. 2. However, the insufficient supply of land source in populous regions restricts the installing of PV systems. Owing to the inherent low energy density characteristics of solar energy, the construction of large-scale PV ground power stations is mostly selected in the waste land or Gobi desert to avoid occupation of arable lands [27], but suffers from superfluous power generation since these places usually possess relatively low load level of production for local consumption.

The scenario of solar integration to agricultural greenhouse in the form of modern solar greenhouse opens a perspective on simultaneously responding to the declining availability of suitable arable land and the imperative for minimum emissions. By placing PV systems on roof top or integrating to greenhouse structure, the large availability of surfaces taken up by greenhouses is able to grow agricultural products below while producing self-consumed energy on the top, which allows the multifunction role of one land [28]. As far as the scale of multi-span greenhouses in China to be concerned (the value is extracted to be 56940.63 ha from 2013, see Fig. 1), they could possibly load more than 17.1 GW polycrystalline silicon modules. In turn, these PV modules could supply more than 25,650 GW h electricity within a year, i.e., the power generated per ha would reach 450 MW h ha^{-1} yr^{-1}. With the incessant progress in designing of more advanced solar greenhouse, plastic tunnel and making the most of non-cultivated land area, the solar integration and application of modern solar greenhouse can be further benefited. So far, China has committed many efforts to explore the integration of solar power to modern greenhouses, and numerous successes have been achieved [29–31], which will be fully discussed in the next section.

3. Application of modern solar greenhouse in China

3.1. Engineering projects

3.1.1. PV greenhouse

In early 2013, the national first 17 PV greenhouses with an installed capacity of 1 MW and total area of 12 ha were constructed in Shouguang County, Shandong, town of vegetables. Then, they were put to use in the end of the year, making them the first on-grid PV greenhouse demonstration project whose annual power generation of up to 1.5 GW h was utilized for self-consumption and the excess transported to nearby residents through the power grid [29,30].

Subsequently, driven by the incentive policy of “Golden Sun project” and facility horticulture related financial supports, as well as the demands for agriculture industrialization by power enterprises, the exploring construction of PV greenhouses is successively conducted in several other provinces such as Hebei, Shanxi, Henan, Shaanxi, Yunnan, Ningxia etc. Table 2 has a summary of the typical PV greenhouse projects distribution in China, many of which have already

Table 1
Annual energy consumption per unit greenhouse area with different loads in China.

Location	Energy load	Annual energy consumption per unit greenhouse area (MJ m^{-2} yr^{-1})	Reference
Jiangsu	Cooling, ventilation	108	[18]
Anhui	Cooling, ventilation, pumps	42 (for two months)	[19]
Shannxi	Cooling, humidifying	15.6 (for two months)	[22]
Daqing	Heating, water pumping	724.9	[20]
Ganzi	Heating, ventilation, lighting	293.9–305.8	[21]
Zhenjiang	Heating	5.4	[23]
Shanghai	Heating	90.7 (for four months)	[24]
Shanghai	Heating, other automatic control devices	119.5	[25]
Beijing	Heating, fans ventilation, water pump	310.9–847.4	[26]

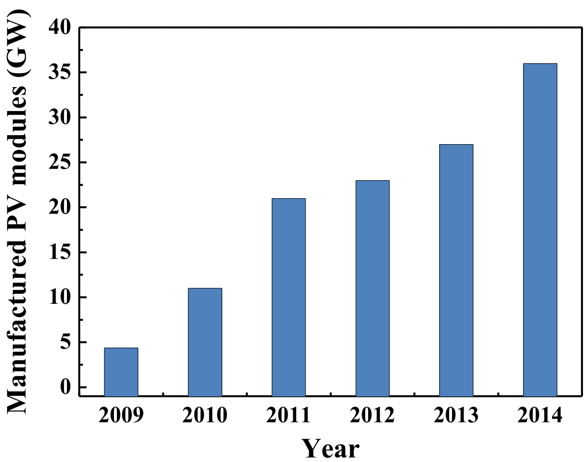

Fig. 2. Manufactured PV modules in China from 2009 to 2014. *Data source*: PV manufactured statistics from China Photovoltaic Industry Association.

Table 2
Summary of typical PV Greenhouse Projects distribution in China.

Construction site	Area (ha)	Capacity (MW)	Progress	Power generation (GWh/year)
Huailai, Hebei	100	20	Constructed	25
Lu'an, Shanxi	167	50	On-grid	60
Yu County, Shanxi	100	15	On-grid	20
Shouyang, Shanxi	93	30	On-grid	36
Neihuang, Henan	67	Phase I: 25	Constructed	35
Yuanjiang, Yunnan	95	40	Constructed	/
Zhongwei, Ningxia	133	50	Constructed	/
Shijiazhuang, Hebei	133	Phase I: 50	Constructed	54.7
Pingquan, Hebei	83	30	On-grid	39.4
Linyi, Shandong	67	Phase I: 20	On grid	22.4
Jimo, Shandong	/	Phase I: 10	On-grid	10
Fenyang, Shanxi	146	50	Constructed	65
Pucheng, Shaanixi	99	40	On-grid	52

been local grid connected.

It is indicated by Table 2 that the overall installed capacities of PV greenhouses in China have ranked tens of megawatts, and several already reached 50 MW. The Lu'an 50 MW PV greenhouse project is the largest on-grid in current, which covers an area about 167 ha and the investment amounts to 74,870,000 $. It includes more than 766 monomer solar greenhouses by adopting 255 W polycrystalline silicon panels as the roof top, and can produce 60 GWh electricity per annum that is estimated to benefits in saving 21,000 t of coal, 770 t of smoke emission and 56,000 t of CO_2 emission. Besides, the economic profits of more than 4,492,000 $/year will be created by the agriculture sector [31,32].

Beyond existing projects, PV greenhouses with larger-scale are being constructed in regions like Hebei, Guangxi, and Wuhan of which the largest capacity reaches up to 120 MW with the annual expected electricity generation of approaching 100 GW h. Additionally, some R & D sectors are also taking actions, such as the Chinese Academy of Sciences (CAS) conducted “Xiaguang Project” in cooperation with the “Photovoltaic Stereo-agriculture Industrialization Project” by Hezhou, Guangxi has been launched and under construction [18].

3.1.2. Solar thermal greenhouse

There are also some other solar thermal greenhouses that have been applied in China's Beijing, Gansu, Xizang, etc. These greenhouses utilize heat-absorbing solar collectors accessed with circulation tubes to heat water for night space heating purpose. The Beijing Solar Heating Greenhouse Project is a demonstration project including 12 pilot modern greenhouses with coverage of 520 m^2 solar collectors [33]. Through the solar heating system, the average temperature can be increased by 4–5 °C. Lately, the Yuteng New Energy Corporation is constructing the largest solar collector integrated glass multi-span greenhouse project in Lasa, Xizang, with total areas of 50000 m^2. So far, phase 1 project is put into operation with mounted collectors of 1500 m^2 and heat collecting efficiency of 41.6% [34].

3.2. Economic evaluation

The economic evaluation including the cost, operating income and the payback time of the combined agriculture and solar system sectors is conducted to assess the potential of the application of modern solar greenhouses in China. Analysis of a Xinjiang PV greenhouse project (total area of 132 ha) based on multi-span structures with roof installation angel at 35° is exemplified as an illustration. The initial cost of this project and the operation parameters are summarized in Tables 3a and 3b, respectively. Costs for the installation include all balance of the system (the concretes, steel frames greenhouses, labour etc. for greenhouse construction; solar modules, switch boxes, inverters etc. for PV system), and the designed time-frame is 20 years set at the expected lifetime of the silicon solar modules. The economic analysis result of the Xinjiang PV greenhouse project is shown in Table 3c, which takes a comprehensive considerations on the effectiveness of agriculture and PV generation.

From Table 3c, it reveals taking about 8.7 years to recover the initial costs. This result is close to the estimation by Gao et al. [35] of the PV greenhouse project in Zhumadian location with the payback period of 7 years despite with deviation to the calculation by Zhao et al. [36] of the Ningxia PV greenhouse project with more than 10 years and by Wang et al. [37] of the Zhoukou PV greenhouse project with 6 years, as a consequence of the differences in the greenhouse locations, scales and the solar resources, etc. Considering the more than 20 years life-span of

Table 3a
The initial cost of the Xinjiang PV greenhouse [83].

Item	cost
Greenhouse installation ($/ha)	680,610
PV system installation ($/w)	1.33

Table 3b
The operation parameters of the Xinjiang PV greenhouse [83].

Sector	Item	Value
Agriculture	Area (ha)	132
	Planting cost ($/ha)	79,404
	Output ($/ha)	139,522
Photovoltaic	Annual utilization hours (h)	1600
	Installed capacities (MW)	50
	Feed-in Tariff ($/kWh)	0.14
	Maintenance cost ($/kWh)	0.039

Table 3c
Economic analysis results of the Xinjiang PV greenhouse.

Item	Agriculture	Photovoltaic
Annual operating cost ($)	10,481,395	3,144,418
Annual income ($)	18,417,309	14,910,533
Annual profit ($)	7,935,914	11,766,115
Annual total profit ($)	19,702,029	
Total cost of investment ($)	170,697,012	
Payback (year)	8.7	
Return on investment (%)	2.12	

PV modules and the relatively shortened time of the return cycle in comparison with the sole PV stations that are mostly over 10 years, there leaves quite profit margins for the integration of PV to greenhouse to make it financially sensible. Although PV construction has long been a troubling problem due to the expensive investment and relatively long payback time, PV module prices have been reported to drop by over 30% in the past five years. Taking the polycrystalline silicon module for example, the price was about 0.87 $/W in 2011 but has had a dramatic declination to less than 0.6 $/W in 2016. With such tendency, more economic efficiency could be exhibited by PV greenhouse installation in the future as a result of the significant reduction in the initial capital cost. Here, if assuming the PV system price reduced by 10%, the above calculated payback period will be shortened to only 8.3 years, and to 7.8 years, 7.4 years by 20% and 30% reduction, respectively.

3.3. Problems and challenges

As a fact, given the considerable achievements acquired by modern solar greenhouses in China as a new technical infrastructure, the complexity in solar technology integration to modern greenhouses and the relatively low industrialized level also bring about problems and challenges. Here, the main challenges of lack of industrial standard, dilemma in subsidy and the technical obstacles are discussed below.

3.3.1. Lack of industrial standard

The differences in load capacities of plastic tunnel, solar greenhouse and multi-span greenhouse raise strict demands for PV installation, roof support system, and fastening of covering materials. In addition, the environmental control and cultivation management of PV greenhouse varies greatly from conventional greenhouse. So far, it is still in lack of a set of mature standardized design theory to guide for PV panels installation and greenhouse management. Moreover, since PV and greenhouse agriculture involve various departments of the National Energy Administration (NEA), Ministry of Agriculture (MOA), National Development and Reform Commission (NDRC), as well as local government with respect to electricity, agriculture, and land and resources, there is great complexity in establishing a unified industrial standard.

3.3.2. Dilemma in subsidy

In 2014, the NEA declared that PV greenhouse project with low-medium voltage of less than 35 kV and capacity within 20 MW listed as distributed PV station but enjoy the feed-in tariff (FiT) of ground-installed station (FiT of distributed PV: 0.062 $/KWh, ground-installed PV: 0.14 $/kWh in class II regions) [13]. This incentive policy promotes the development of PV greenhouses to some extent but also triggers some adverse consequences like driving the pursuit for maximum PV generation profit regardless of agricultural production. Therefore, the interests of farmers and relative departments are seriously damaged. Evaluation mechanism and restraint policy are in deficiency to inhibit the arbitrary expansion. Concurrently, there is no unified subsidy scheme for agricultural part.

3.3.3. Technical obstacles

The most prominent problem manifested by PV greenhouse is the irreconcilable competition between PV roofs and plants. Since conventional crystalline silicon modules are opaque to sunlight, even for the fast growing thin-film amorphous modules the transmittance is only 10–20%, it will form permanent shadows zones projected by PV roofs and consequently lead to a poorly lit environment. This is a big problem for heliophiles growth.

As for solar thermal greenhouse, water tank is widely adopted for storage of solar energy captured by solar collectors. But limited by the storage capacity of water medium (10–50 kWh/t) as well as the negative effect of solar seasonality and the day-night cycle [38], this kind of solar thermal greenhouse is usually not able to cover the heat load all the year round.

These technical obstacles could incur the insufficient and inefficient utilization of solar power for modern solar greenhouse. In order to solve these problems and better enhance exploiting of sun flux, exploration of advanced solar utilization technology for greenhouse application is of great necessity. Therefore, a large quantity of researches has been conducted, which will be studied in the following section.

4. Prospects of advanced solar technology for modern solar greenhouse in China

The poor heating-preserving performance of current solar thermal greenhouse and the shadowing effect in PV greenhouse has directed a series of researches in academia on utilization of advanced solar technology for applicable integration. These researches are mainly organized around three aspects: PT (Photothermic) utilization technology, PV utilization technology, and light management, and the specific sub-classifications are shown in Fig. 3. Here, the main subjects studied by Chinese scholars are presented.

4.1. PT utilization technology

4.1.1. Long-term thermal energy storage

Regarding the disadvantages of the short-term/diurnal thermal storage (via water tank) in solar thermal greenhouse, a great supply of efforts has been made to study long-term thermal energy storage (LTES) including the borehole thermal energy storage (BTES) [24,25], aquifer thermal energy storage (ATES) [26] and phase change material (PCM) storage [39,40], which are able to optimize the heating performance of solar thermal greenhouse through balancing energy demand and supply on months or even seasonal basis and little affected by consecutive gloomy and cold days.

The performance of a 2304 m^2 solar-heated greenhouse equipped with BTES system in Shanghai (Fig. 4) was analyzed by Xu et al. [24]. This system utilized approximately 4970 m^3 soil directly under the greenhouse embedded with 130 vertical U-type heat exchangers to store the excess solar heat captured by a 500 m^2 solar collector. Heat was charged to ground from Apr. 2012 to Nov. 2012 and in the next

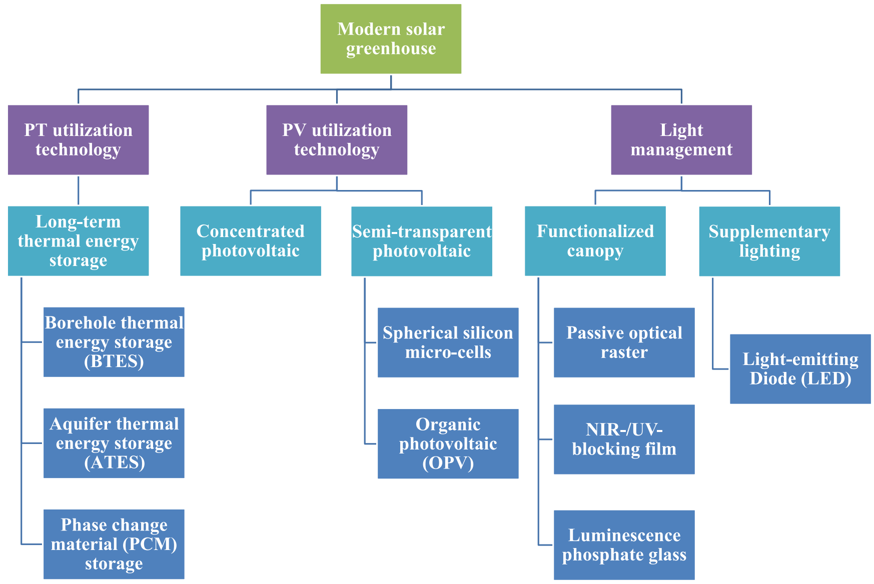

Fig. 3. Classification of advanced solar utilization technology for modern solar greenhouse.

winter period from Dec. 2012 to Mar. 2013, the discharging process began. Results showed that this system with only solar energy input could cover all the heating loads, and during the heating season, an interior air temperature with 13 °C higher than the ambient atmosphere was maintained. Thereby, energy consumption would decrease in the system because of the efficacy in solar utilization. Similar BTES system to collect summer heat for compensation of heat supply insufficiency in winter was also applied in two pilot greenhouses located at Tongji University and Xinbang Blueberry Planting Base, Shanghai respectively for blueberry production [25]. Compared with conventional underground heating systems, it had three operation modes to solve the heat storage-releasing problem without heat pumps so the cost was economically feasible. The energy saving was estimated to be 27.8 kWh/(m^2 typical greenhouse area. year) if the indoor air temperature of the greenhouse was kept above 12 °C throughout the year, and the benefit with 120% higher production as well as 50–100% higher price for blueberry production could be also obtained. Since the capability of heat exchanger is limited by the temperature of underground soil layer, shallow aquifers is another source for solar energy extraction by heat pumps. Chai et al. [26] conducted a study on the performances of two solar greenhouses integrated with a ground source heat pump system (GSHP) in Shangzhuang Agricultural Experiment Station, Beijing. This system contained three water circuits including the groundwater drawing and refilling circle, the GSHP energy enhancing circle, and the greenhouse heating circle (Fig. 5). Solar energy was stored in shallow groundwater, constituting the source of shallow geothermal energy to charge the fan-coil units for indoor heating or cooling. Though such system was more energy-consuming than in [24,25], heating was proved to have high coefficient of performance equal to 3.83 and 3.91 respectively in two greenhouses during the testing winter period. Moreover, in comparison with gas heating method it had lower daily cost and better environmental performances, e.g., lower CO_2 emissions, but the latent water pollution and land subsidence problems led by inappropriate refilling of groundwater was to be further investigated.

Lately, phase change material (PCM) technology is regarded promising for storing solar thermal as a latent storage way, which can be 5–14 times than sensible storage methods with water or rock [41]. PCM is a substance with a high heat of fusion, and by melting and solidifying at a certain temperature, large amounts of heat is absorbed or released when the material changes from solid to liquid and vice versa. Ling et al. [39] discussed and analyzed the thermal performance

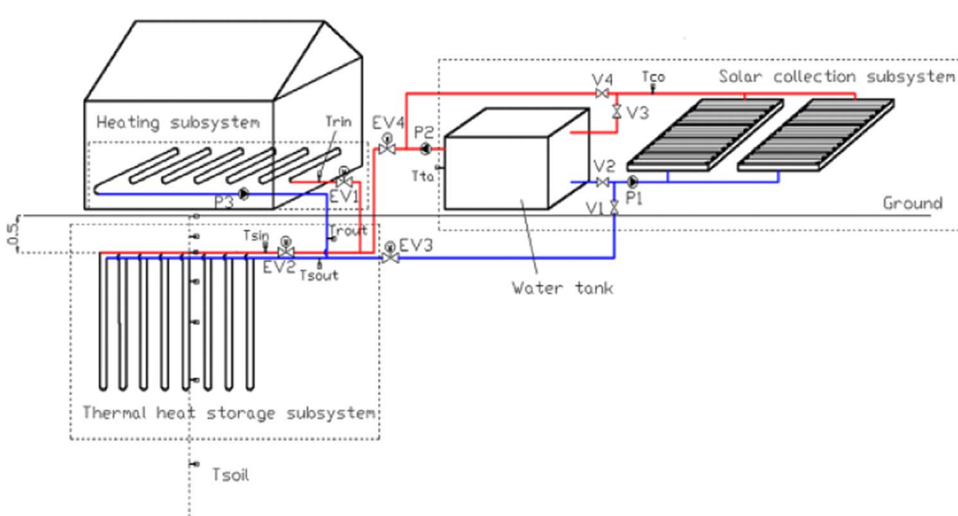

Fig. 4. Schematic diagram of borehole thermal energy storage (BTES) system [24].

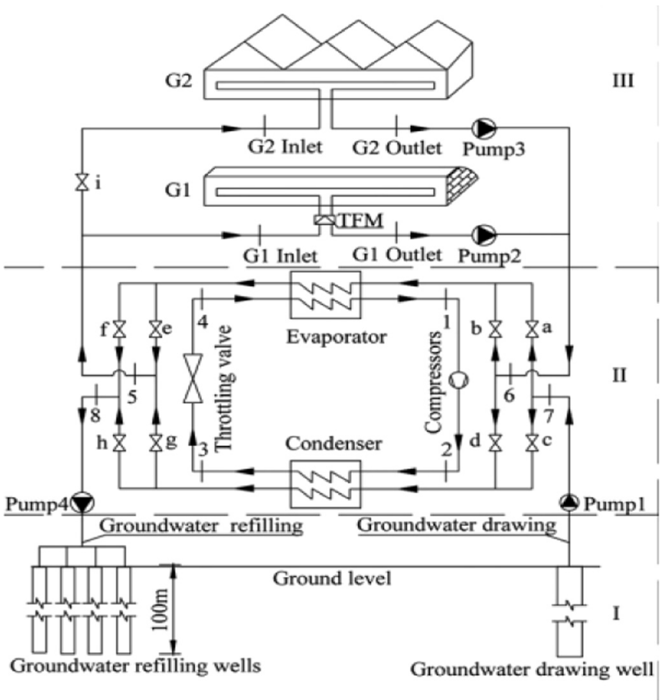

Fig. 5. Schematic diagram of aquifer thermal energy storage (ATES) system [26].

of an Active-passive triple PCM wall (APTPCMW) as the north wall for heat storage. This APTPCMW consisted of PCM wallboards, concrete hollow blocks and insulation layer in turn from inside to outside, inside the hollow blocks were several parallel vertical air tunnels connected with solar concentrators placed on the wall top. In a test, the active heat storage was 9.43 MJ m^{-3} with 17.3% of it stored in PCM layer when carried out for 8 h, and heat release was 9.28 MJ m^{-3} after 16 h. Therefore, the heat storage capacity was significantly improved by APTPCMW, and heat can be released efficiently during the nighttime as well. In another work by the same author, the long-term (61 days) effect of a typical greenhouse located in Beijing with 0.05 m thick GH-20 PCM wallboards incorporated to the north wall was evaluated [40]. A series of performance indicators investigated experimentally or numerically suggested that PCMs would exert a positive contribution to the indoor thermal condition enhancement of greenhouses over a long period.

4.2. PV utilization technology

Due to the inherent shadowing effect in PV greenhouse, there have been many reports investigating different arrangements of PV panels' position and spacing to acquire a proper distribution of inner sunlight [6,42,43]. Cossu et al. [6] found that with optimum spacing, the coverage of the PV roof could be adjusted lower than 20% and thus exert little influence on cucumber growth. And based on simulation, Fatnassi et al. [42] proposed that the mean solar radiation transmission in the Venlo greenhouse surpasses that in the Asymmetric greenhouse and the checkerboard arrangement of photovoltaic panels is more favorable to spatial distribution of sunlight as compared to the straight-line arrangement.

Although such arrangement optimization has demonstrated positive effects, the practical improvement is still limited. Nowadays, along with the fast development of concentrator systems and semiconductor materials, two novel PV technologies including concentrated photovoltaic and semi-parent photovoltaic have also achieved rapid growth. Owing to their potential in concentrating sunlight for individual PV panel, and cascade utilization of solar energy for both solar modules and the plants below, respectively, wide interests are attracted on their integration to modern greenhouses.

4.2.1. Concentrated photovoltaic

Concentrated photovoltaic is an approach for generating reasonable amount of electricity with limited solar cell areas. More sunlight radiation will be intercepted by the solar modules hence less coverage of PV rooftop is needed, which is beneficial for homogeneous indoor illumination and uniform growth of plants. On the other hand, in cases of shade plant cultivation, diffuse light is more favorable than direct insolation then this excess part can be utilized by concentrated photovoltaic through converting to electrical energy [44,45].

Feng et al. [46] designed and analyzed a kind of compound parabolic concentrator (CPC) as greenhouse's transparent cover, Fig. 6 shows its schematic diagram. It included many CPCs made of highly transparent plexiglass on which bottom sticking by photovoltaic cells. Since the transmittance changed with the variation of incident light angel as a result of the changing of light paths by the cover, oblique incident light can be used for lighting and vertical incident light can be concentrated on cells for generating electricity. Experimental results showed that the lowest transmittance of 32% together with the highest 6.2 W/m^2 electric output per unit area was attained when there was strong sunshine at noon; while in the morning and afternoon, the transmittance of cover material could reach 60%, which meant this cover was conducive to both plant growth and electric generation. When getting high output power by the concentrated irradiation, the significant rise in solar cell temperature would also in turn reduce the cell efficiency and lead to cell degradation [47]. Subsequently, a compound parabolic concentrator-photovoltaic/thermoelectric hybrid power generation system (CPC–PV/TE) consisting of CPC, PV/TE hybrid system and flat heat pipe was established based on the characteristics of greenhouse in Northeast China [48]. Of this system, CPC converged light to photovoltaic cells attached with thermos-electric power generator modules enabling the conversion of generated excess heat to electric power. Flat heat pipe was attached to the bottom of thermo-electric power generator modules with water flow to effectively transfer the rest of the heat. This hybrid system was proved valuable to increase the efficiency of individual power generation module and realize the comprehensive utilization of solar energy. As indicated by the result, the generated power and the efficiency of CPC-PV/TE hybrid system increased by joining of thermos-electric power generation modules, and a maximum power output of 125.98 W, efficiency of 20.06% were gained.

4.2.2. Semi-parent photovoltaic

Semi-parent photovoltaic is an effective approach to balance

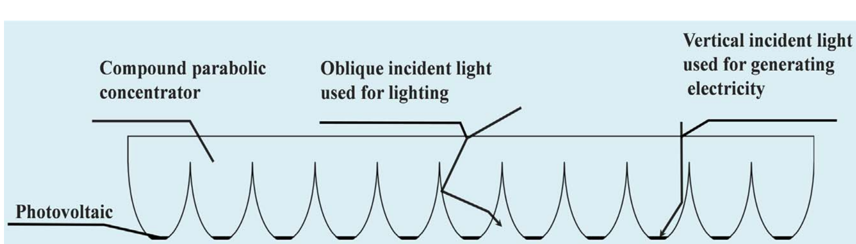

Fig. 6. Transparent entity compound parabolic concentrator [46].

electricity production and light transmissivity as they shade merely a fraction of the incident light and allow maximum usage of the remnant radiation to reach the plants. Products based on semi-transparent amorphous silicon or CIGS thin films have already been commercialized in the market, though their transparency is still far from excellence to create a quite bright illumination distribution. Thereby, Cossu et al. [49] developed a prototype composed by 4800 spherical silicon micro-cells sandwiched between glass plates with a coverage area of 2.3% for greenhouse roof application. It was found that the yield factor was slightly higher than the conventional multi-crystalline silicon module.

Until the emergence of organic photovoltaics (OPV) and their preliminary exploration for window integration, the real application of semi-parent photovoltaic is limited [50]. OPV owns the advantage of a unique semiconductor structure that can be manipulated and tuned to the optimal spectral absorbance for both plants and PV modules. Actually, for plant photosynthesis, not the full sunlight spectrum is necessary. Of the global solar radiation entering the greenhouse interior space, there are ultraviolet (UV), photosynthetic active radiation (PAR) and near-infrared (NIR), and the PAR ranging from 400 nm to 700 nm is exactly what plants require during the photosynthesis [51]. Fig. 7**a** depicts the absorption spectrum of carotenoid and chlorophyll as the most important photoreceptors in plant. It indicates that photosynthesis mainly occurs at the range of 400–520 nm and 610–720 nm, with the former containing violet, blue and green bands, and the latter contains red bands [52]. Emmott et al. [50] first assessed the potential of OPV technology for PV greenhouse application by performing a detailed techno-economic analysis. Five commercially available polymer OPV materials were evaluated considering their efficiency and spectrally-resolved transparency, and their absorption coefficients were shown in Fig. 7**b**. Except for the P3HT material that absorbs primarily within the PAR region, the others show peaks off the characteristic absorption of plants, which indicates their potential to harness light not required for plant growth. Thereafter, Yang et al. [53] demonstrated a tandem photonic crystal based visible transparent OPV device with an average absorption efficiency of 51.5% and transmittance of 40.3% in the PAR range. Results illustrated that this device can realize the maximum utilization of sunlight for crops due to the significantly increased transmittance spectrum, and the crop growth factor could reach 41.9%. Nevertheless, the current OPV technology is still immature to fully realize its integration to modern greenhouse, but considering its light-weight and flexible nature for rapidly retro-fitting existing greenhouse structure, there is a prospect on condition that OPV materials with higher efficiency and transparency are developed.

4.3. Light management

In some cases, low lighting condition can't be avoided during the course of seasonality and day-night cycle, and considering the negative shading of greenhouse structure (especially in PV greenhouse), light supplement is an indispensable choice [8]. Beyond that, excessive light intensity could also do harm to plant's normal growth. Therefore, much work has been made in both light transmission control (to lower thermal load) and active light supplement, which are exemplified by the latest research of functionalized canopy and LED lighting, respectively.

4.3.1. Functionalized canopy

Canopy refers to the covering or structural material (e.g. plastic film or glass) used in modern greenhouse which could also play key roles in determining light transmission with varied composition, constitution, and property. To control the direct solar radiation with greater flexibility, many researchers have proposed or fabricated different functionalized canopies for greenhouse application. Korecko et al. [54] utilized a kind of passive optical rasters as greenhouse glass to realize the control of direct radiation depending on the incident angle of sunlight. It was shown that light would transmit in winter for heating purpose whereas in summer, light was reflected to reduce heat load in the interior. Sometimes, the ultraviolet and infrared in the solar spectrum are useless to biological process and even could result in a decrease of plant matter, thus, thin-film coatings like near-infrared (NIR)- and ultraviolet (UV)- blocking materials are developed. Chen et al. [55] fabricated a kind of UV-blocking film by modified Vinyl–POSS material, the average transparency measured at the ranges of UV-a and UV-b spectra was about 45.43–48.71%, indicating that these films can protect greenhouse plants from UV-a and UV-b. Beyond the NIR-/UV-blocking thin film, the functionalized canopy made of luminescence material is also capable of reducing unnecessary ultraviolet or infrared light whilst possesses another function of converting the unnecessary ultraviolet, visible, and/or infrared photons into red and/or blue photons that are exactly required for plant photosynthesis (Fig. 8). Researchers have successfully manipulated certain red and/or blue light emissions by luminescence material modifications. Ming et al. [56] prepared a highly efficient luminescence material with the compositions of P_2O_5–Li_2O–Al_2O_3–Sb_2O_3–MnO–Eu_2O_3–Er_2O_3–Yb_2O_3 on phosphate glass, which was an efficient converter of red emission by converting ultraviolet, visible, infrared photons into red photons and displayed strong red emission to the naked eye under the illumination of sunlight. Therefore, the quality of sun flux utilization is improved for glass greenhouse. In his earlier work [57], new reddish orange luminescent Mn^{2+}/Eu^{3+} co-doped phosphate glasses were prepared, and the emission spectra in the 550–800 nm wavelength regions have been observed, which was also valuable for the photosynthesis of green plants. Furthermore, dual red and blue emissions for crop cultivation was achieved by Lv et al. [58] with Mn^{2+}/Sn^{2+} co-doped PZL glasses, and the ratio of red to blue light emission could be tuned by adjusting the content of ion ratio.

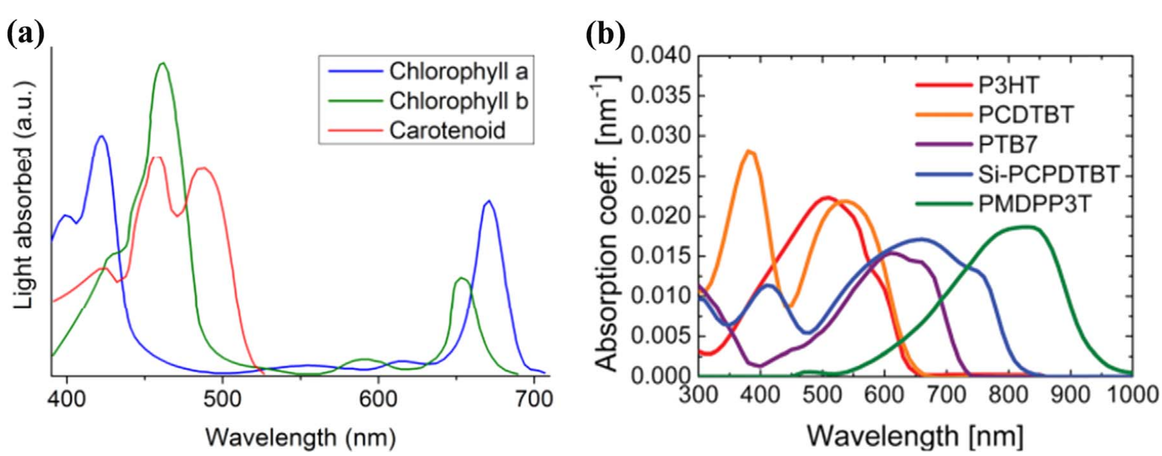

Fig. 7. Absorption spectrum of **(a)** chlorophyll and carotenoid in plant [52], **(b)** five commercially available polymer materials of organic photovoltaic [50].

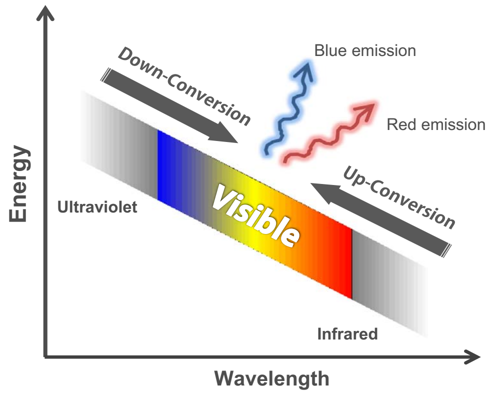

Fig. 8. Light conversion mechanism of luminescence glass.

4.3.2. LED supplementary lighting

As an energy-efficient, economic and sustainable lighting technology [59–62], LEDs could be driven easily by PV power and possess great potential for future modern solar greenhouse lighting. LEDs are a type of semiconductor diode capable of providing pulses light by frequent "on" and "off" switching so as to reduce electrical energy consumption [52,63], and moreover, allowing the adaptation of light intensity and control of spectral composition optimized to plant growth. Up to now, LEDs have been introduced in nursery of several plant species such as rice seedlings, lettuces, peppers, cucumbers, tomatoes, flowers and part traditional Chinese medicines in China, and wide researches have been conducted in exploration of the effects of LEDs lighting condition (light quality, intensity, and photoperiod) on the physiology of these plant kinds, which are summarized in Table 4.

Light quality of LEDs is important in regulating plant's morphology, physiology and microstructure. Literature studies demonstrated that the combination of red (R) and blue (B) light is effective in producing most plant species for it best drive photosynthetic metabolism [64–74]. Specifically, red light is usually regarded as the basal lighting component, which can result in elongation of stem [64,66], increase of leaves [75,76] and stimulate the development of photosynthetic apparatus [70]. References [67,72,75] suggested that red light is also important in promoting accumulations of biomass and chemicals, e.g., regulating the synthesis of soluble sugar, carotenoids, phenolic and oxalate. Blue light is important for leaf expansion and inhibition of hypocotyls [64], and blue-light-grown plants show photosynthetic characteristics similar to those of plants grown under high irradiance, which promotes chloroplast development and chlorophyll synthesis [72,73], increases carotenoid, vitamin C [68] whilst cutting down nitrate content [65]. Additionally, light quality plays a key role during different growth stages of certain plant. Hao et al. [77] found that mini-cucumber leaf was significantly taller and had a high chlorophyll index with blue LED inter-lighting, while the harvested fruits grown under white and red light treatment showed better visual qualities. Chang et al. [65] suggested that RCB LED irradiation be used at the seedling stage for lettuce for yielding high chl-a and low nutrient contents, and the adoption of RBUV-A and RCB light during the vegetative stage was recommended for developing the shoot fresh mass of leaf lettuce. Light intensity is also crucial in control of photosynthesis, nutrients accumulation and plant's morphology determination. Ma et al. [66] reported that increasing the light intensity from 500 lx to 2500 lx would significantly accelerate the growth of rice seedling's root length, number, and result in healthier and greener leaf. Several experiments of leaf lettuce [64,65,75,78], leaf tomato [70] and cucumber [77] have also shown the requirement of moderate to high photosynthetic photon flux (PPF) among 150–300 μmol m^{-2} s^{-1}. Photoperiod can exert significant effect on blossom, fruit yield, as well as some other physiological activities. Li et al. [69] found that the average dry weight and chlorophyll florescence parameters of pepper fruit increased when turning the light duration from 2 h (18:00–20:00) to 6 h (18:00-00:00). But in terms of the cultivation of cut chrysanthemum, short-daylight is more favorable for seedling flowering as reported that 12 h light/12 h dark for 43 days was the optimal light option for quick budding and bloom [71].

All these investigations would allow the determination of species specific optimal light quality, intensity, and photo-period, which are beneficial for promotion of LED supplementary lighting for future application in modern solar greenhouses.

5. Conclusion

Modern solar greenhouse is an important initiative in China's protected cultivation history for it benefits in energy saving, pollution reduction, and comprehensive competitiveness of modern agriculture improvement, especially in this low carbon production era. An overview of China's progress towards the development of modern solar greenhouses is presented in this paper. The most obvious obstacles of China's modern solar greenhouse are characterized by the poor heating-preserving performance (of solar thermal greenhouse) and the shadowing effect (of PV greenhouse), and a series of advanced solar utilization technologies to mitigate the effects of heat loss, shadowing, and poor light condition for applicable integration have been researched. Specifically, the long-term thermal energy storage technique is an effective way to optimize the solar thermal greenhouse heating performance (PT utilization). Concentrated photovoltaic and semi-parent photovoltaic can better balance the light utilization of both plants and solar cells in comparison to their silicon counterpart though less economically competitive (PV utilization). Functionalized canopy enables sunlight transmission control to lower the thermal load whilst LED lighting represents a more energy-efficient approach for the active light supplement (light management).

Researches on application of these advanced solar technology has been proved effective to promote solar energy utilization in modern solar greenhouses and provide an insight into their integration prospect. With further improvement in the economic performance, as well as the establishment of supportive policy and incentive mechanism, modern solar greenhouses in China will have a promising prospect to lead a sustainable development.

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Table 4
Effect of LED lighting condition on physiology of different plant species.

Plant		Radiation condition	Effect on plant physiology	Reference
Crops	Rice seedling (*Oryza sativa*)	Red (660 nm) and Blue (460 nm) LEDs in different ratios and light intensities, 6 h/d	R/B ratio (8:1) and light intensity of 2500 lx promoted rice stem elongation and growth	[66]
	Rice cultivars ('Wuyunjing 7' and 'Kangyou 63')	Red (658 nm) LEDs and Blue (460 nm) LEDs with ratio 1:1, total PPF maintained at 80 μmol m^{-2} s^{-1}, 12 h/d	Increased leaf soluble sugar and sucrose contents	[67]
Vegetables	Leaf lettuce (*Lactuca sativa* var. *crispa*)	RCB (42.8%, 30.0%, 27.2%) and RBUV-A (52.9%, 37.0%, 10.1%) LEDs, PPF: 300 ± 12 μmol m^{-2} s^{-1}, 18 h/d	Increase shoot fresh mass, yield high chl-a and low nitrate contents	[65]
	Chinese bayberry (*M. rubra Sieb.* and *Zucc.* cv. *Biqi*)	Blue (470 nm, 40 μmol m^{-2} s^{-1}) LEDs alone	High contents of sucrose, fructose, and glucose	[79]
	Muskmelon 'Elizabeth'	Red (650 nm) LEDs	Increased leaf area, leaf number, total dry mass and root/shoot ratio Compare to blue treatment	[76]
	Chinese cabbage (*Brassicacamprestis* L.)	Blue plus red LEDs (B:R=1:8) at PPF of 80 μmol m^{-2} s^{-1}, 12 h/d	The addition of blue LEDs increased vitamin C and chlorophyll	[68]
	Baby leaf lettuce (*Lactuca sativa* L. cv. Red Cross)	Blue (476 nm) or Red (658 nm) or FR (734 nm) added to fluorescent lamps, total PPF:300 μmol m^{-2} s^{-1}, 16 h/d	Anthocyanins and carotenoids were increased by B LEDs, R LEDs increased phenolics and FR LEDs promoted leaf growth and dry weight	[78]
	Pepper (*Capsicum frutescens* L., Sujiao No. 5)	Red (660 nm) and B (460 nm) in different ratios and durations, PPF: 65 μmol m^{-2} s^{-1}	Lower R/B ratio (6:3) and duration of 6 h caused greater fresh weight of fruits	[69]
	Lettuce (*Lactuca sativa* var.*crispa* 'Green Oak Leaf')	White LEDs (105 μmol m^{-2} s^{-1}) plus supplemental LEDs (30 μmol m^{-2} s^{-1})	Lettuce supplemented with white and red appeared compact and vigorous	[75]
	'Green Oak Leaf' lettuce (Lactuca sativa var. crispa)	Red LEDs or Blue LEDs added to FL, total PPF (133 ± 5 μmol m^{-2} s^{-1}), 14 h/d	Improved morphology, greater biomass and pigment contents	[64]
	Mini-cucumber (*Cucumis sativus* L. 'Picowell')	Blue (14.5 μmol m^{-2} s^{-1}) LEDs with HPS (145 μmol m^{-2} s^{-1}), 12–20 h/d	Significant higher fruit yield	[77]
	Chinese kale (*Brassica oleracea* var. *alboglabra* Bailey)	Blue (470 nm, 30 μmol m^{-2} s^{-1}) LEDs, 16 h/d	Reduction of undesirable gluconapin content	[80]
	Leaf of Cherry tomato (*Solanum lycopersicum* Mill)	Monochromatic or mixture of LEDs, total PPF (320 μmol m^{-2} s^{-1}), 12 h/d	Net photosynthesis was increased by B, RB, and RBG treatments	[70]
Flowers	Cut Chrysanthemum 'Reagan' (*Chrysanthemum morifolium* Ramat)	Compound LEDs with R/B ratio 1:2 and R/B ratio 2:1, PPF (57μmol m^{-2} s^{-1})	R/B ratio 1:2 favored quick budding and bloom of seedlings, limited inductive photoperiod was 43d at short daylight (12 h light /d)	[71]
	Honeysuckle (*Lonicera japonica*)	Red (625 nm) LEDs, 12 h/d for 30d	Increased plant height and blossoms	[81]
	Cymbidium tracyanum var. huanghua × *Cymbidi*um mastersii	Red (625 nm), blue (475 nm) and green (530 nm) LEDs with ratio 4:2:1, 800 lx with photoperiod of 14 h/d	Higher contents of chlorophyll and carotenoids	[72]
Chinese herbs	*Ganoderma lucidum* mycelium	Blue LEDs (24 W)	Beneficial for mycelium polysaccharides synthesis	[82]
	(*Dendrobium of ficinale*)	50% blue (464 nm) LEDs and 50% red (640 nm) LEDs	Best effects on growth, chlorophyll synthesis, and dry mass and sugar accumulation	[73]
	Kimura et Migo (*Dendrobium of ficinale*)	Monochromatic or mixture of LEDs, total PPF (50 μmol m^{-2} s^{-1})	Maximal root length obtained under red light, thickest stem diameter by blue light and higher chlorophyll by red blue mix light	[74]

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