ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Controlled-Environment Agriculture—Review

Photothermal-Management Agricultural Films toward Industrial Planting: Opportunities and Challenges

Song Zhang, Zhang Chen, Chuanxiang Cao, Yuanyuan Cui *, Yanfeng Gao *

School of Materials Science and Engineering, Shanghai University, Shanghai 200444, China

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Greenhouse
Photothermal management
Passive radiative cooling
Light scattering

ABSTRACT

As indispensable parts of greenhouses and plant factories, agricultural covering films play a prominent role in regulating microclimate environments. Polyethylene covering films directly transmit the full solar spectrum. However, this high level of sunlight transmission may be inappropriate or even harmful for crops with specific photothermal requirements. Modern greenhouses are integrated with agricultural covering materials, heating, ventilation, and air conditioning (HVAC) systems, and smart irrigation and communication technologies to maximize planting efficiency. This review provides insight into the photothermal requirements of crops and ways to meet these requirements, including new materials based on passive radiative cooling and light scattering, simulations to evaluate the energy consumption and environmental conditions in a greenhouse, and data mining to identify key biological growth factors and thereby improve new covering films. Finally, future challenges and directions for photothermal-management agricultural films are elaborated on to bridge the gap between lab-scale research and large-scale practical applications.

1. Introduction

Recent research has estimated that global food production must be increased by approximately 70% [1] to sustain a global population of 9 billion by 2050. Controlled-environment agriculture (CEA) has been recognized as a reliable strategy to enhance global food production [2]. Greenhouses and plant factories are the major components of CEA systems. In these systems, the microclimate (i.e., light and temperature) can be regulated by means of heating, ventilation, and air conditioning (HVAC) systems [3], as shown in Fig. 1(a) [4]. Moreover, smart irrigation technologies can be integrated to maximize irrigation efficiency and reduce water waste, as shown in Fig. 1(b) [5]. Communication technologies can also be employed to optimize crop-management information in HVAC systems, as shown in Fig. 1(c) [6]. However, HVAC systems require enormous energy consumption, which can account for 70%–85% of the total operating costs of a greenhouse [7]. The light intensity in a greenhouse is not only lower but also spatially inhomogeneous compared with external conditions, especially for lower-lying leaves, which are exposed to rather dim light conditions. "Vertical agriculture" refers to the practice of planting crops in vertically stacked layers. It typically includes CEA to optimize plant growth, as well as soilless farming techniques such as hydroponic and aerial cultivation. Although vertical agriculture, as shown in Fig. 1(d) [8]) maximizes the utilization of light, approximately 30% of the operating costs are spent on electricity for supplemental lighting [9].

The history of the greenhouse dates back to 14–37 Anno Domini (AD) [10], as shown in Fig. 2(a). Early greenhouse cladding materials were mainly glass, which is characterized by its strength and high light transmission. However, the installation cost of glass is relatively high, and its high thermal conductivity results in poor thermal insulation efficiency at night. Subsequently, polyethylene was developed as a covering material for greenhouses. There are three main types of greenhouses in China: solar greenhouses, multi-span greenhouses, and plastic shed greenhouses as shown in Fig. 2(b)–(d) [11–13]). The regional distribution and growing trend of greenhouses in China are shown in Fig. 2(e)[14]. Most greenhouses are constructed with polyethylene film as a covering material, as it is corrosion resistant, durable, soft, and lightweight. Nevertheless, the single C–C and C–H bonds in polyethylene molecules result in high sunlight transmission, causing excessively high temperatures inside the greenhouses [15].

---

* Corresponding authors.
E-mail addresses: cui-yy@shu.edu.cn (Y. Cui), yfgao@shu.edu.cn (Y. Gao).

https://doi.org/10.1016/j.eng.2023.06.016

Please cite this article as: S. Zhang, Z. Chen, C. Cao et al., Photothermal-Management Agricultural Films toward Industrial Planting: Opportunities and Challenges, Engineering, https://doi.org/10.1016/j.eng.2023.06.016

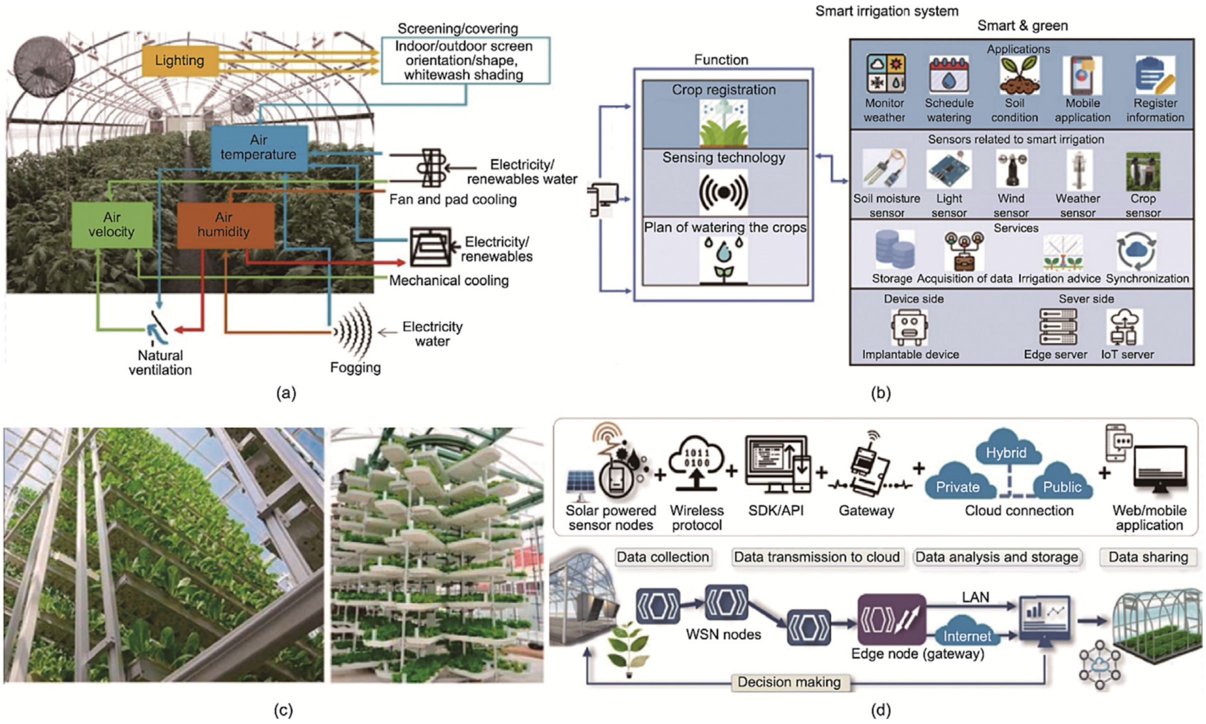

Fig. 1. Intelligent management of modern agriculture. (a) An intelligent irrigation system (reproduced from Ref. [4] with permission). (b) A microclimate-management system (reproduced from Ref. [5] with permission). (c) Images of vertical farming (reproduced from Ref. [6] with permission). (d) An Internet of Things (IoT)-based data acquisition and monitoring system for greenhouse environment (reproduced from Ref. [8] with permission). SDK: software development kit; API: application programming interface; WSN: wireless sensor networks; LAN: local area network.

Passive radiative cooling materials have attracted tremendous interest for thermal management in buildings, because they are effective at regulating indoor heat by reflecting sunlight and heat to a colder external space through the infrared transmission window of the atmosphere. In fact, greenhouses are living buildings for crops and, when these novel materials are applied in greenhouses, they can provide a favorable choice for appropriate temperature control [16]. Furthermore, the use of a light-scattering film is a viable option to expand the illuminated area for plants in greenhouses during periods of insufficient sunlight. Direct sunlight can be scattered so that the sun-irradiated area of leaves in different positions is expanded [17].

In the following sections, a brief introduction is first provided to the photothermal requirements of crops, followed by an overview of passive radiative cooling and light-scattering films employed in agriculture. Then, a simulation is proposed to evaluate the energy consumption and environmental conditions in a greenhouse. Finally, challenges and opportunities are presented for the future use of photothermal-management films.

2. Photothermal requirements of crops

Crops are influenced by light both directly and indirectly [18]. Direct influence refers to the fact that light is a signal during plant photomorphogenesis, such as seed germination, tissue growth, and cellular differentiation [19], while indirect influence refers to crops' use of light as an energy source in photosynthesis [20]. Three key parameters of light—namely, intensity, uniformity, and quality—should be taken into consideration in crop growth [21].

Light quality refers to the color or wavelength of light. As shown in Fig. 3(a) [22], sunlight is composed of 6%–7% ultraviolet (UV) light (<380 nm), approximately 42% visible light (380–780 nm), and 51% near-infrared (NIR) light (780–2500 nm) [22]. NIR light provides heat for crop growth and development. The 400–700 nm range is known as photosynthetically active radiation (PAR). Blue (430–500 nm) and red (630–770 nm) light are the most effectively utilized during the photosynthesis of green leaf crops, due to the primary absorption of chlorophyll [23].

Crops can be categorized as having high, medium, or low light requirements based on their lighting needs for normal growth and development [25]. Typically, increases in the net photosynthesis rate are positively correlated with light intensity [26]. Sun-loving crops exposed to insufficient light will experience decreased photosynthesis and decreased growth and glucose production, causing their foliage to appear weak [27].

The uniformity of light encompasses both temporal and spatial distributions. Sunlight commonly reaches greenhouses as parallel light and is therefore easily blocked by obstacles or plant canopies [28,29]. In contrast, scattering improves the distribution of light from different angles into the inner plant canopy, where it is absorbed and utilized for photosynthesis [30].

Temperature is another dominant environmental factor that regulates crop growth. There are three cardinal temperature points in plant growth: the minimum, optimum, and maximum temperature [31]. Various physiological processes, including photosynthesis, respiration, water transport, hormone secretion, and supersession, are influenced by temperature [32]. Crops can be damaged at temperatures that are too high or too low, and growth and development are optimal only at the optimum temperature [33]. As shown in Fig. 3(b) [24] illustrates the energy-transfer mechanism between a greenhouse and its surroundings, and optical photos of the interior of a greenhouse are shown in Fig. 3(c) [24].

For example, the strawberry is a typical temperature-sensitive fruit, with the soluble solid content (SSC) serving as the primary parameter for assessing its internal quality [34]. Research has found that the average air temperature during strawberry ripening negatively correlates with the strawberry's firmness and SSC, although the extent of reactivity varies by cultivar [35]. After three

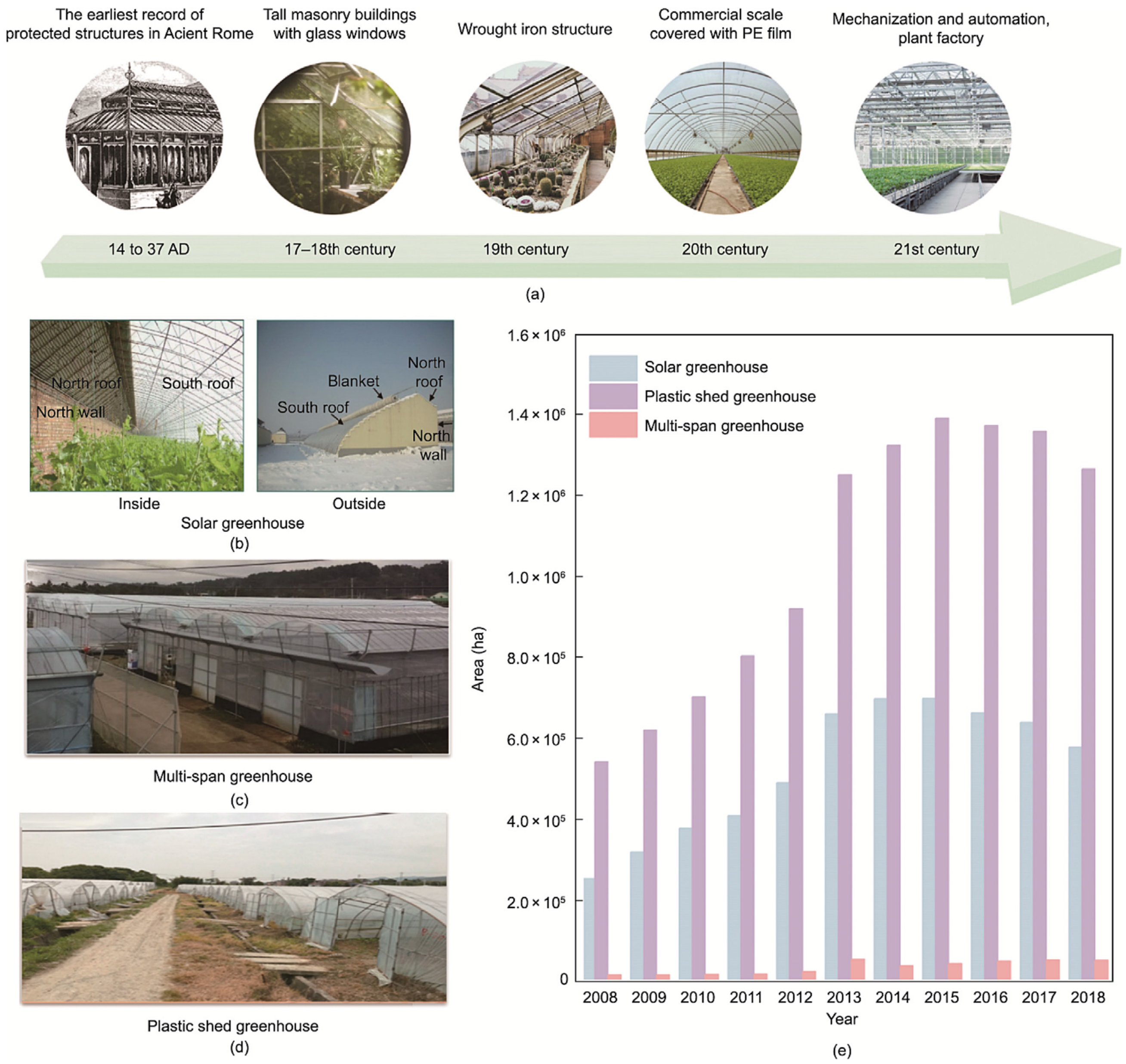

Fig. 2. History, types, and development trends of greenhouses. (a) A brief history of greenhouses. (b) Solar greenhouse (reproduced from Ref. [14] with permission). (c) Multi-span greenhouse (reproduced from Ref. [15] with permission). (d) Plastic shed greenhouse (reproduced from Ref. [16] with permission). (e) Trends in the three types of greenhouses in China (data obtained from Ref. [17]). PE: polyethylene.

weeks of flowering, strawberries grown at 15 °C have a higher SSC than those grown at 22 °C [36]. Furthermore, strawberries grown in high carbon dioxide concentrations and higher temperatures tend to contain higher levels of polyphenols and antioxidants [37].

Secondary metabolites such as phenylpropane compounds are ubiquitous in plants and play an important role in plant growth, especially in response to adversity stress, such as in avoiding damage, resisting diseases, and acting as signal transduction molecules [38]. For example, the intensity and duration of high temperature significantly affects the phenylpropane content of grapes at different stages of fruit development [39]. In some insightful reviews [40–42], the mechanisms of ambient temperatures on crops have been extensively studied. Nevertheless, further effort must be devoted to comprehending the relevant underlying mechanisms, including genes, molecules, organs, tissues, signals, and other aspects.

3. Passive radiative cooling materials for greenhouses

Passive radiative cooling materials are commonly used in buildings to create a comfortable indoor environment and save energy [40,41]. They also exhibit similar benefits when applied in agricultural greenhouses [42,43]. The interactions between light and a material surface include reflection, transmission, and absorption, where the sum of these three parts is equal to 100% [44]. The transmittance of an opaque material is typically 0% [45]. Furthermore, Kirchhoff's law of thermal radiation proposes that the absorptivity of each wavelength amounts to the emissivity when the object is in a thermal equilibrium state [46]. A detailed description of the theory of passive radiative cooling is provided in Bijarniya et al.'s review [47].

The heat balance of radiative cooling materials is described by Eq. (1), where P_r represents the radiative power emitted by the

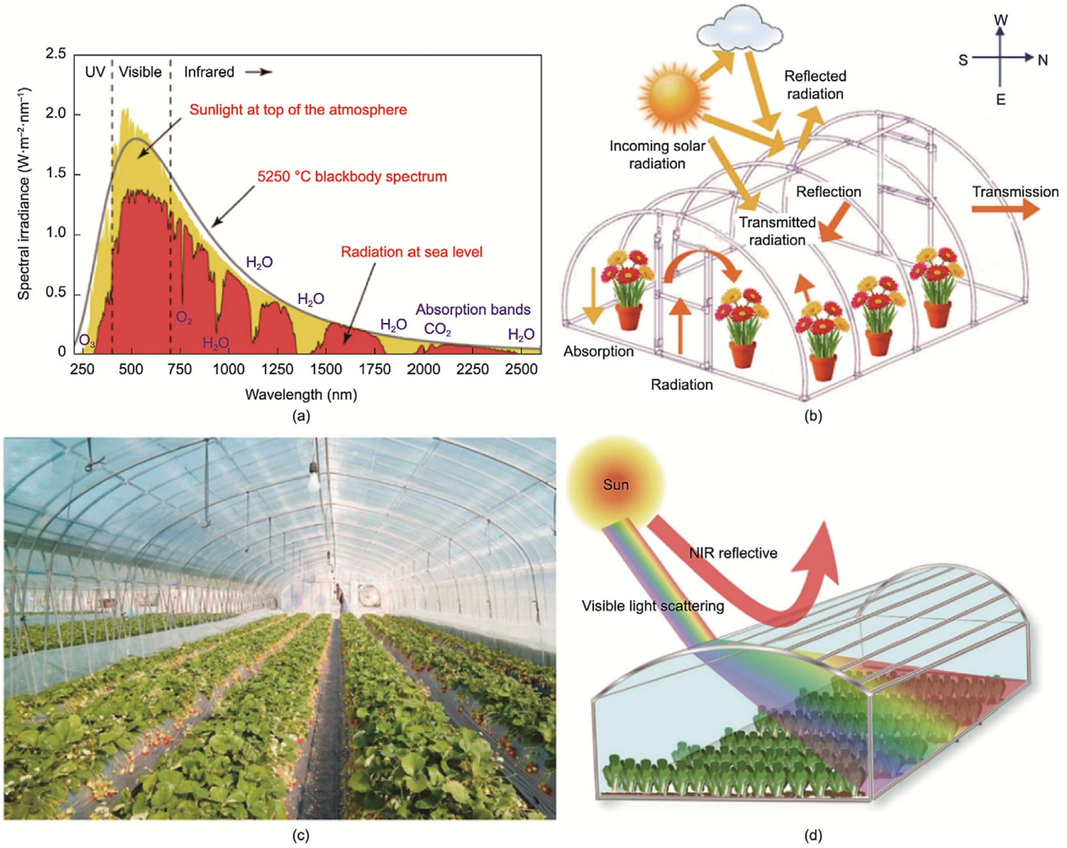

Fig. 3. Solar radiation and greenhouses. (a) The solar spectrum in space and on the surface of the earth (reproduced from Ref. [22] with permission). (b) Energy exchange via radiation in a conventional greenhouse (reproduced from Ref. [24] with permission). (c) Inside view of a vegetable greenhouse (reproduced from Ref. [24] with permission). (d) A diagram of visible light scattering and NIR light reflected by a greenhouse's covering.

matter and P_a is the radiative power absorbed from the incident atmospheric atmosphere. P_{sun} is the absorbed solar power, and the power loss caused by conduction and convection is expressed as P_{conv}. In general, the absorption rate is reduced by increasing the reflectivity of solar radiation. Altogether, there are two main considerations to achieve passive radiative cooling: One is increasing the emissivity of the atmospheric window, and the other is enhancing the infrared reflectance [48]. The mechanism of greenhouse covering films with infrared reflection is shown in Fig. 3(d).

$$P_{net} = P_r - P_a - P_{sun} - P_{conv}. \tag{1}$$

Certain ceramic particles that have a large band gap, high refractive index, and low extinction coefficient are favorable for backscattering solar light [49]; examples include titanium dioxide (TiO_2) [50], barium sulfate ($BaSO_4$) [51], zirconia (ZrO_2) [52], silicon dioxide (SiO_2) [53], zinc sulfide (ZnS) [54], magnesium oxide (MgO) [55], and zinc sulfide (ZnO) [56]. Perylene, copper(II) phthalocyanine, perylene diimide derivatives, and tricyclodecane dimethanol diacrylate are the main organic additives [57]. The matrix materials are carefully screened for passive radiative cooling, and a polymer without attenuation in the full solar spectrum is preferred, such as polyethylene (PE) [58], polyvinylidene fluoride (PVDF) [59], polydimethylsiloxane (PDMS) [60], poly(methyl methacrylate) (PMMA) [61], or polyester (PET) [62]. Better passive radiative cooling effects can be achieved by constructing ordered porous arrays on material surfaces [63]. Other important influences on radiation cooling include particle size, volume fraction, and film thickness [64]. When using a material outdoors, it is important to consider its durability, and creating a hydrophobic surface is an effective way to enhance its longevity [65].

Another popular matrix material is transparent wood (TW), which has high optical transmittance. In transparent wood, most of the lignin has been selectively removed and then replaced with a suitable polymer such as PMMA [66]. Functional particles, including antimony-doped tin oxide (ATO) [67], ZnO [68], and tungsten-doped VO_2 [69], are often integrated to improve the efficiency of the radiative cooling. TW is hard and inflexible and thus unsuitable for greenhouse covering, especially for tunnel-like greenhouses. Passive radiative cooling materials usually require high reflectivity and high emissivity in the atmospheric window region. The higher the refractive index (n) is at the air–material interface, the stronger the backscatter and the greater the reflection will be. The extinction coefficient (k) is a physical quantity that characterizes the ability of a material to absorb light; a higher k value indicates that the electromagnetic radiation decays rapidly in the material and is gradually absorbed by the material. In addition, passive radiative cooling materials should provide a wide energy band greater than solar photon energy (0.49–4.13 eV) to avoid absorbing solar radiation [70]. Therefore, when selecting highly efficient passive radiative cooling materials, it is necessary to consider the material's n value, k value, and bandgap width. Excellent chemical stability, low cost, large surface area, and high-speed production are also key considerations for screening materials. The most widespread greenhouse covering material in the world is low-density polyethylene (LDPE) film; a radiative cooling polyethylene monolayer film with silica as an additive increases reflectivity by 7% [71]. Nonetheless, studies of passive radiative cooling materials manufactured with LDPE have been applied to textiles for personal thermal management [72] and temperature regulation for buildings or transport [73] more widely than for agricultural greenhouses at present.

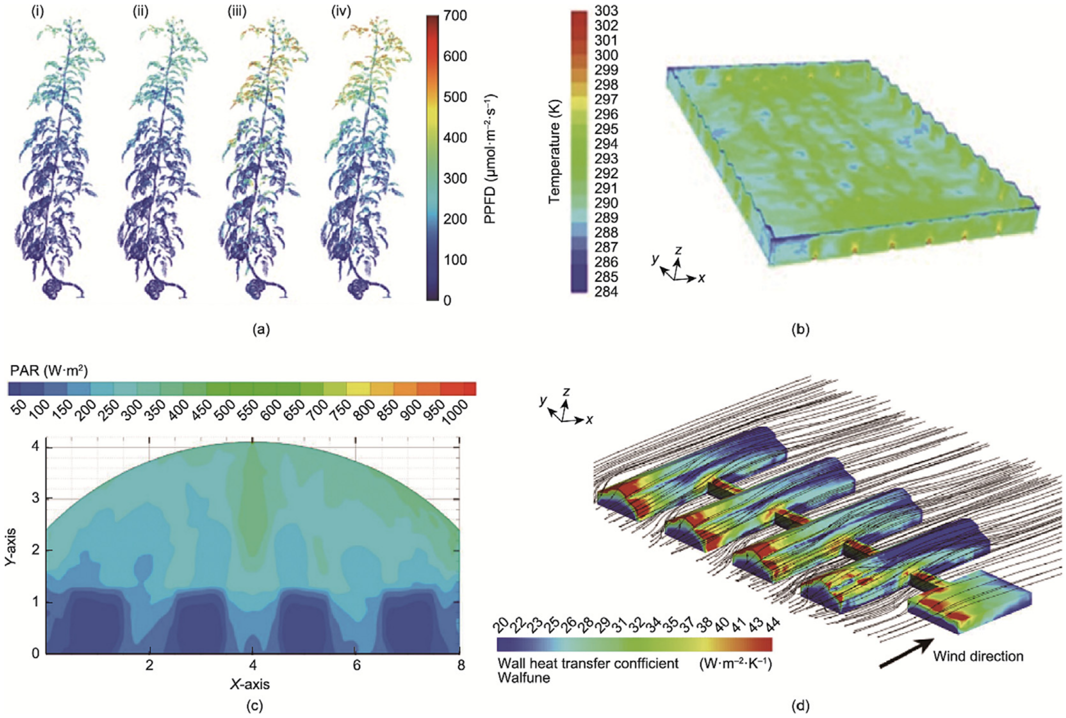

Fig. 4. Simulation of solar radiation and the growth environment. (a) Simulated light distribution on 3D tomato plant models according to film diffuseness and regional solar radiation ((i) low irradiance, high diffuse radiation fraction (LIHD), haze 10%; (ii) LIHD, haze 90%; (iii) high irradiance, low diffuse radiation fraction (HILD), haze 10%; and (iv) HILD, haze 90%), PPFD: photosynthetic photon flux densities (reproduced from Ref. [79] with permission). (b) Simulated temperature distribution in a greenhouse (reproduced from Ref. [98] with permission). (c) PAR radiation isocontours inside a greenhouse (reproduced from Ref. [99] with permission). (d) Air path lines over a greenhouse and surface heat transfer coefficient over the walls (reproduced from Ref. [100] with permission).

The use of NIR reflective materials in greenhouses shows promising application potential in certain cases. Mutwiwa et al. [74] employed NIR reflective materials for cultivating tomatoes in greenhouses located in central Thailand. Their research findings suggested that NIR reflection can effectively decrease the greenhouse temperature by 2.8 °C. Furthermore, the growth parameters—including plant height, leaf area index, and dry matter content of tomatoes—remained largely unaffected. Chen and Shen [75] reported achieving a 31.4% increase in asparagus average spear yield by planting asparagus in greenhouses with NIR reflection diffusion coatings in summer. The researchers found that the NIR reflective diffusion coating reduced the average temperature in the greenhouse by 1.8, 1.9, and 0.7 °C in June, August, and September, respectively, with the highest temperature decreasing by 6.0, 7.1, and 3.7 °C, respectively [76]. Research also indicates that, compared with ordinary commercial films, the temperature is 9 °C lower in greenhouses covered by infrared reflective films, and cucumber yields are 24.3% higher [77].

4. Light-scattering materials for greenhouses

When light-scattering film is used as a greenhouse cover (as shown in Fig. 3(d)), it is greatly affected by the local climate, sunlight conditions, and even the type of crop grown in the greenhouse. Therefore, an acceptable approach to assess light-scattering films under assorted light environments is to use a ray-tracing simulation with three-dimensional (3D) plant models [78]. The complex optical interactions between the internal and external environments of a greenhouse and the microlight environment of the canopy can be displayed in a ray-tracing simulation. For example, a higher haze brought more uniform light distribution and a higher photosynthetic rate for tomatoes, as shown in Fig. 4(a) [79].

Light scattering occurs when light passes through particles, generating an oscillating charge, and is then reradiated in various directions. The extent and deflection of the scattering depends on the frequency of the light and the size of the particles. The relationship between particle size and incident wavelength can be expressed by the size parameter (x), as shown in Eq. (2):

$$x = \frac{2\prod r}{\lambda} \tag{2}$$

where r is the particulate radius and λ is the wavelength [80]. When x is far less than 1 or when the particle size is less than 1/10 of the incident light wavelength, a kind of elastic scattering called Rayleigh scattering will occur. When x is close to 1 or the particle size is greater than λ/10, then Rayleigh scattering transitions into anisotropic inelastic scattering, called Mie scattering [81].

Light-scattering materials can generally be divided into two types: surface-relief and volumetric materials [82]. Surface-relief scattering materials rely on their microstructures, such as abundant uneven structures and rough textures [83]. The incident light deviates from its direction when light passes through the surface with the microstructure. Surface-relief scattering films usually possess high transmittance. The fabrication of surface-relief scattering films frequently involves electrospraying, etching, and embossing processes, which are complicated and expensive [84]. Volumetric materials can scatter light by means of particles dispersed inside a matrix; the manufacturing process for volumetric materials is simpler and more efficient than that for surface-relief materials [85].

Many light-scattering coatings, blocks, or film materials have been prepared based on the theory of scattering. Volumetric-type scattering materials are prepared by dispersing particles into matrices with different refractive indices. The particles in the matrices usually consist of microparticles such as SiO_2 [86], $CaCO_3$ [87], $BaSO_4$ [88], polystyrene (PS) [89], PMMA [90], or ZnO [91], while the polymers used for the matrices include PE [92], PET [93], or PC [94]. According to the American Society for Testing and Materials (ASTM) D1003 standards [95], haze is generally used to assess the degree of light scattering. Haze is expressed as the percentage of incident light scattered more than 2.5° by a light-scattering material [96]. Light-scattering materials have been widely used in electronic displays, lighting engineering, projection imaging [97], and other technical fields to improve the uniformity of light intensity and eliminate glare. Simulation of solar radiation and the growth environment was shown in Fig. 4 [98–100].

The diffusion ratio within greenhouses is crucial for modeling studies, particularly when evaluating the impact of scattering film on crop growth. Understanding the behavior of diffused light in greenhouses is crucial for improving the accuracy and reliability of predictions regarding radiation absorption by the canopy and photosynthesis. A five-year record of a large amount of solar and diffuse radiation data from October 1999 to December 2004 suggested that the transmittance of diffusing light is less susceptible to the diurnal evolution of the angle of incident light than the transmission of direct light [101].

The yield of spinach under diffused film (57% haze) was found to be 22.3% higher than that under fully transparent film when light-scattering film was used to grow vegetables in real greenhouses [8]. Other experimental research has indicated that the production of different crops (e.g., tomato, cucumber, and roses) improved by 10% under diffuse light conditions [102]. In winter, light diffusion was found to enhance amino acid contents in lettuce leaves by up to 1.15 times [103]. Zheng et al. [104] conducted a study on the application of scattering films with varying haze levels (20% and 29%) as coverings for solar greenhouses. Their findings revealed that leaves exposed to higher haze levels showed a significant increase in net photosynthesis compared with those exposed to lower haze levels (19.0% and 27.2%, respectively). Moreover, the 29% haze area resulted in a 5.5% increase in yield for high stem-density tomatoes and a 12.9% increase for low stem-density tomatoes when compared with the 20% haze area. Di Mola et al. [17] conducted a greenhouse study in Portici, Naples, Italy, and made a significant discovery: The utilization of light-scattering film can increase spinach yield by 22% and improve the soil plant analysis development index by 4.6%, all while leaving the leaf chlorophyll content unaffected.

5. Simulation of energy consumption and environmental conditions

The energy consumption and environmental conditions of a greenhouse are influenced by a complex set of external and internal factors. The external factors are climate and geographical location, while the internal factors include building structures and materials, heating equipment, evaporative cooling systems, ventilation, carbon dioxide supply, and artificial lighting. To save research and development (R&D) costs and achieve the lowest energy consumption requirements, it is necessary to simulate the energy consumption of greenhouses in order to thoroughly investigate the best cooperation between photothermal management films and various systems. Rasheed et al. [105] used a Transient System Simulation (TRNSYS)-18 program to study a multi-span greenhouse building energy simulation (BES). They found that cooling energy requirements can be reduced by up to 25% by using a shading screen in summer. An energy consumption simulation presents significant advantages in screening greenhouse materials. Yu et al. [106] used Energy Plus software to simulate phase-change materials (PCMs) on greenhouse energy conservation, combined with experimental data. They found that the heat load in spring, autumn, summer, and winter can be reduced by 6.4, 5.8, 3.4, and 2.9 GJ, respectively. The annual total heating load can be reduced by 18.5 GJ, which is equivalent to 4.7% annual energy savings. The accumulated energy savings in spring, summer, and autumn were 9%.

An energy consumption and environmental simulation of a greenhouse involves several parts, including the establishment of a greenhouse model, a carbon dioxide supply system, the design of an HVAC system [107], and computational fluid dynamics (CFD), which can be performed using software or algorithms for simulation and result analysis [108]. A CFD simulation can be used to analyze and solve problems of temperature (As shown in Fig. 4(b) [98]), PAR distribution (Fig. 4(c) [99]), and air path lines (As shown in Fig. 4(d) [100]). A greenhouse that faces south can have its largest wall area exposed to the sun to obtain the most solar radiation, and the ventilation system can be installed on the east and west walls. A thickly layered wall can be built with heat-storing material and insulation material to prevent heat loss [109].

The interior environment of a greenhouse, such as the temperature, air quality and humidity, is controlled by airflow patterns. CFD is a type of simulation for analyzing the spatiotemporal distribution of flow velocity and temperature, and it can be used to simulate fluid flow conditions and heat [110], mass, and momentum transfer with the purpose of optimizing agricultural design. Exhaustive flow patterns and heat transfer fluxes can be calculated accurately using CFD. Baxevanou et al. [100] used the finite volume method and Ansys Fluent CFD code for a two-dimensional (2D) simulation of transmission phenomena, aerodynamics, and heat radiation transmission in four wavelength bands (UV, PAR, NIR, and infrared radiation) in tunnel-type tomato greenhouses with side openings. In their work, models of greenhouses were covered with ethylene–vinyl acetate (EVA) resin, three-layer coextruded polyethylene, and PVC films. Their results showed that the EVA covering material provided the longest suitable environment for tomato planting compared with the other three over a period of one year. Nevertheless, the researchers did not explain this phenomenon in terms of material properties. Kumar et al. [111] developed a quasi-static steady-state 3D simulation model and conducted CFD simulations. They found that the use of earth-to-air heat exchangers (EAHEs) resulted in a decrease of 7–8 °C in greenhouse temperature during the summer and an average increase of 4–5 °C in winter. Yu et al. [112] studied the thermal performance of a 3D tomato model built in SolidWorks using CFD simulation; they noted that the study of 3D models can provide guidance for reasonable ventilation and assist in designing a thermal environment suitable for tomato plant growth. Knowledge about CFD has been introduced more extensively in reviews [98]. Despite all these studies, more CFD simulations aimed at greenhouses covered with photothermal management films need to be proposed.

6. Opportunities and challenges

Statistical data show that, in January 2019, the area of greenhouse vegetable planting was 4.968×10^5 ha worldwide [113]. In China, the total area of planting facilities, tunnel-like greenhouses, solar greenhouses, and multi-span greenhouses will exceed 2.0×10^6 ha by 2025. The Ministry of Agriculture and Rural Affairs of the People's Republic of China has set the goal of accelerating facility agriculture, which suggests that the regional layout of planting facilities will be more reasonable, and the structural types will be optimized [114]. Photothermal management agricultural films provide valuable opportunities, given the trends of global food insecurity and the pursuit of carbon neutrality. For sun-

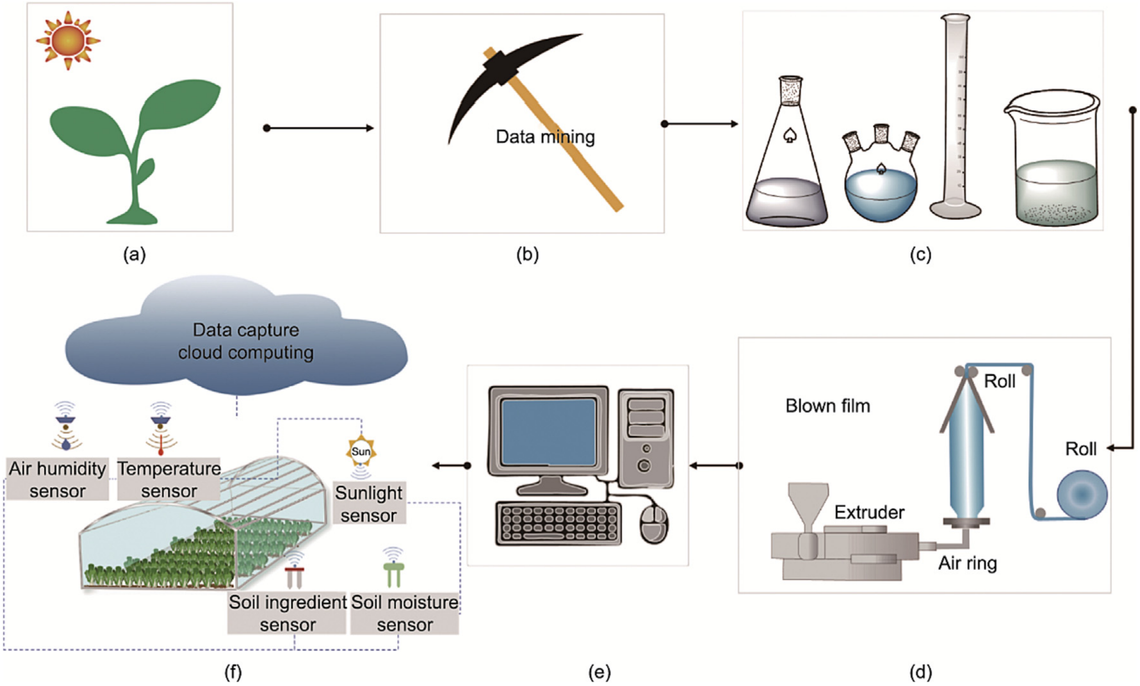

Fig. 5. Research and preparation process for functional agricultural film. (a) Determine the photothermal requirement of crops. (b) Perform data mining to identify the primary factors that affect biological growth. (c) Design and synthesize the functionalmaterials. (d) Manufacture the photothermal management film. (e) Simulate the energy consumption and environmental conditions. (f) Apply in greenhouses, collecting environmental data.

loving crops, a larger exposure area can increase their photosynthetic rate and promote growth rate, so light-scattering film is more conducive to their growth. For shade-loving crops, a larger exposure area is not needed. All crops have a most suitable temperature growth range. Once the local temperature exceeds the maximum growth temperature, infrared reflective film is more suitable for creating a growth microenvironment than a sunshade and active ventilation.

Greenhouses are an irreplaceable measure to solve food insecurity in the future. With the rapid development of automatic irrigation, soilless culture, information management, and mechanical automation [115], remarkable progress has been made in the photothermal and microclimate management of greenhouses. Greenhouse planting has become more efficient, modernized, standardized, and intelligent. However, some areas remain to be further explored. The architectural design concept of human comfort should be integrated into greenhouses, and all intelligent and mechanized designs of greenhouses should be based on physiological knowledge of crops. Therefore, a deeper understanding of how crops respond to the environment will help in the evaluation, design, and control of greenhouse materials.

Data mining can be a powerful means of identifying the key factors that affect biological growth. For example, Mamatha Bai et al. [116] used data mining technology, including bisecting K-means, DBSCAN, OPTICS, hierarchical complete linkage, and STING, to analyze the results on key factors in growth obtained in recent decades in order to predict the best environmental parameters for the maximum yield of ragi, peanuts, and rice in Karnataka. The most popular forecasting models are the random forest, neural network, linear regression, and gradient boosting tree models. Multiple models are usually used in parallel to predict and compare the results [117].

Much remains to be done in photothermal management covering films for greenhouse crops. As shown in Fig. 5, it is imperative to design, manufacture, and demonstrate photothermal management films based on better knowledge of the environmental requirements of specific crops. An effective way of increasing the cooling effect of passive radiation is to improve the infrared reflectance of greenhouse cover materials. A spectrally selective film with NIR reflection and visible light scattering is deemed more suitable than other available options for creating a microenvironment conducive to crop growth, given current knowledge of the photothermal requirements of crops. It is believed that the critical process in increasing greenhouse crop yields is the design of materials involving micro- and macroscale features. The refractive index and particle size have the greatest influence on the infrared reflection and visible light scattering. Here, the key issue is how to prepare particles with an anticipatory refractive index and an appropriate size. A significant factor in deciding the properties of a material is the interface between the organic matrix and inorganic particles, and modifying this interface involves modification of the particle surface and optimization of the processing technology. Eventually, the comprehensive performance of photothermal management film must be verified through demonstration applications; then, environmental data in greenhouses and the quality and yield of the crop must be collected, to establish the relationships and interactions among covering films, the environment, and crops.

Compliance with ethics guidelines

Song Zhang, Zhang Chen, Chuanxiang Cao, Yuanyuan Cui, and Yanfeng Gao declare that they have no conflict of interest or financial conflicts to disclose.

Acknowledgements

The authors gratefully acknowledge the support from the National Natural Science Foundation of China (52372088) and the Innovation Program of Shanghai Municipal Education Commission (2019-01-07-00-09-E00020).

References

[1] Ananno AA, Masud MH, Chowdhury SA, Dabnichki P, Ahmed N, Arefin AME. Sustainable food waste management model for Bangladesh. Sustain Prod Consump 2021;27:35–51.

[2] Cohen AR, Chen G, Berger EM, Warrier S, Lan GH, Grubert E, et al. Dynamically controlled environment agriculture: integrating machine learning and mechanistic and physiological models for sustainable food cultivation. ACS Est Eng 2022;2(1):3–19.

[3] Engler N, Krarti M. Review of energy efficiency in controlled environment agriculture. Renew Sustain Energy Rev 2021;141:110786.

[4] Ghoulem M, El Moueddeb K, Nehdi E, Boukhanouf R, Kaiser CJ. Greenhouse design and cooling technologies for sustainable food cultivation in hot climates: review of current practice and future status. Biosyst Eng 2019;183:121–50.

[5] Obaideen K, Yousef BAA, AlMallahi MN, Tan YC, Mahmoud M, Jaber H, et al. An overview of smart irrigation systems using IoT. Energy Nexus 2022;7:100124.

[6] Shao Y, Li J, Zhou Z, Hu Z, Zhang F, Cui Y, et al. The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings. Build Environ 2021;195:107766.

[7] Anifantis AS, Colantoni A, Pascuzzi S. Thermal energy assessment of a small scale photovoltaic, hydrogen and geothermal stand-alone system for greenhouse heating. Renew Energy 2017;103:115–27.

[8] Shamshiri RR, Bojic I, van Henten E, Balasundram SK, Dworak V, Sultan M, et al. Model-based evaluation of greenhouse microclimate using IoT-Sensor data fusion for energy efficient crop production. J Clean Prod 2020;263:121303.

[9] Weaver GM, van Iersel MW, Velni JM. A photochemistry-based method for optimising greenhouse supplemental light intensity. Biosyst Eng 2019;182:123–37.

[10] Walters KJ, Behe BK, Currey CJ, Lopez RG. Historical, current, and future perspectives for controlled environment hydroponic food crop production in the United States. HortSci 2020;55(6):758–67.

[11] Tong G, Christopher DM, Li T, Wang T. Passive solar energy utilization: a review of cross-section building parameter selection for Chinese solar greenhouses. Renew Sustain Energy Rev 2013;26:540–8.

[12] Ha T, Kim J, Cho BH, Kim DJ, Jung JE, Shin SH, et al. Finite element model updating of multi-span greenhouses based on ambient vibration measurements. Biosyst Eng 2017;161:145–56.

[13] Zhang Z, Sun D, Tang Y, Zhu R, Li X, Gruda N, et al. Plastic shed soil salinity in China: current status and next steps. J Clean Prod 2021;296 126453.

[14] Greenhouse data sharing platform [Internet]. Beijing: Institute of Facility Agriculture, Planning and Design Institute, Ministry of Agriculture and Rural Affairs of the People's Republic of China;2014[cited 2023 May 1]. Available from: http://data.sheshiyuanyi.com/.

[15] Kissin YV. Polyethylene: Carl Hanser Verlag. Munich: Hanser Publishers; 2021.

[16] Lu X, Xu P, Wang HL, Yang T, Hou J. Cooling potential and applications prospects of passive radiative cooling in buildings: the current state-of-the-art. Renew Sustain Energy Rev 2016;65:1079–97.

[17] Di Mola I, Ottaiano L, Cozzolino E, Sabatino L, Sifola MI, Mormile P, et al. Optical characteristics of greenhouse plastic films affect yield and some quality traits of Spinach (Spinacia oleracea L.) subjected to different nitrogen doses. Horticulturae 2021;7(7):200.

[18] Briat JF, Gojon A, Plassard C, Rouached H, Lemaire G. Reappraisal of the central role of soil nutrient availability in nutrient management in light of recent advances in plant nutrition at crop and molecular levels. Eur J Agron 2020;116:126069.

[19] Legris M, Ince YC, Fankhauser C. Molecular mechanisms underlying phytochrome-controlled morphogenesis in plants. Nat Commun 2019;10:5219.

[20] Shafiq I, Hussain S, Raza MA, Iqbal N, Asghar MA, Raza A, et al. Crop photosynthetic response to light quality and light intensity. J Integr Agric 2021;20(1):4–23.

[21] Wu BS, Hitti Y, MacPherson S, Orsat V, Lefsrud MG. Comparison and perspective of conventional and LED lighting for photobiology and industry applications. Environ Exp Bot 2020;171:103953.

[22] Ghosh TK, Prelas MA. Solar Energy. In: Ghosh TK, Prelas MA, editors. Energy Resources and Systems: Volume 2: Renewable Resources. Dordrecht: Springer, Netherlands; 2011. p. 79–156.

[23] Saleem MH, Rehman M, Zahid M, Imran M, Xiang W, Liu LJ. Morphological changes and antioxidative capacity of jute (Corchorus capsularis, Malvaceae) under different color light-emitting diodes. Braz J Bot 2019;42(4):581–90.

[24] Gorjian S, Calise F, Kant K, Ahamed MS, Copertaro B, Najafi G, et al. A review on opportunities for implementation of solar energy technologies in agricultural greenhouses. J Clean Prod 2021;285:124807.

[25] Cossu M, Yano A, Solinas S, Deligios PA, Tiloca MT, Cossu A, et al. Agricultural sustainability estimation of the European photovoltaic greenhouses. Eur J Agron 2020;118:126074.

[26] Pan T, Wang Y, Wang L, Ding J, Cao Y, Qin G, et al. Increased CO_2 and light intensity regulate growth and leaf gas exchange in tomato. Physiol Plant 2020;168(3):694–708.

[27] Yang B, Tang J, Yu ZH, Khare T, Srivastav A, Datir S, et al. Light stress responses and prospects for engineering light stress tolerance in crop plants. J Plant Growth Regul 2019;38(4):1489–506.

[28] Liu A, Xu D, Henke M, Zhang Y, Li Y, Liu X, et al. Determination of the optimal orientation of Chinese solar greenhouses using 3D light environment simulations. Remote Sens 2022;14(4):912.

[29] Timmermans GH, Hemming S, Baeza E, van Thoor EAJ, Schenning APHJ, Debije MG. Advanced optical materials for sunlight control in greenhouses. Adv Opt Mater 2020;8(18):2000738.

[30] Emmel C, D'Odorico P, Revill A, Hörtnagl L, Ammann C, Buchmann N, et al. Canopy photosynthesis of six major arable crops is enhanced under diffuse light due to canopy architecture. Glob Change Biol 2020;26(9):5164–77.

[31] Andrade JA, Cadima J, Abreu FM. Modeling germination rate and cardinal temperatures of seven mediterranean crops. J Crop Improv 2018;32 (6):878–902.

[32] Dusenge ME, Duarte AG, Way DA. Plant carbon metabolism and climate change: elevated CO_2 and temperature impacts on photosynthesis, photorespiration and respiration. New Phytol 2019;221(1):32–49.

[33] Chen Z, Galli M, Gallavotti A. Mechanisms of temperature-regulated growth and thermotolerance in crop species. Curr Opin Plant Biol 2022;65:102134.

[34] Xie D, Liu D, Guo W. Relationship of the optical properties with soluble solids content and moisture content of strawberry during ripening. Postharvest Biol Technol 2021;179:111569.

[35] Menzel C. Higher temperatures decrease fruit size in strawberry growing in the subtropics. Horticulturae 2021;7(2):34.

[36] MacKenzie SJ, Chandler CK, Hasing T, Whitaker VM. The role of temperature in the late-season decline in soluble solids content of strawberry fruit in a subtropical production system. HortSci 2011;46(11):1562–2156.

[37] Balasooriya HN, Dassanayake KB, Seneweera S, Ajlouni S. Impact of elevated carbon dioxide and temperature on strawberry polyphenols. J Sci Food Agric 2019;99(10):4659–69.

[38] Geissman TA. The metabolism of phenylpropane derivatives in plants. In: Lozano BA, Ballou CE, Blank F, Charles Evans W, Geissman TA, Goodwin TW, editors. Der stoffwechsel sekundärer pflanzenstoffe/the metabolism of secondary plant products. Berlin, Heidelberg: Springer Berlin Heidelberg; 1958. p. 543–59.

[39] Lecourieux D, Kappel C, Claverol S, Pieri P, Feil R, Lunn JE, et al. Proteomic and metabolomic profiling underlines the stage- and time-dependent effects of high temperature on grape berry metabolism. J Integr Plant Biol 2020;62 (8):1132–58.

[40] Bijarniya JP, Sarkar J, Maiti P. Review on passive daytime radiative cooling: fundamentals, recent researches, challenges and opportunities. Renew Sustain Energy Rev 2020;133:110263.

[41] Yu X, Chan J, Chen C. Review of radiative cooling materials: performance evaluation and design approaches. Nano Energy 2021;88:106259.

[42] Liu CH, Ay C, Tsai CY, Lee MT. The application of passive radiative cooling in greenhouses. Sustainability 2019;11(23):6703.

[43] Kernpkes F, Stanghellini C, Hemming S, Dai J. Cover materials excluding near infrared radiation: effect on greenhouse climate and plant processes. In: International Workshop on Greenhouse Environmental Control and Crop Production in Semi-Arid Regions; 2008 Oct 20–24; Tucson, AZ, USA. Korbeek-Lo: ISHS; 2008. p.477–82.

[44] Dai G, Xia X, Hou G. Transmission performances of solar windows exposed to concentrated sunlight. Sol Energy 2014;103:125–33.

[45] Ao X, Hu M, Zhao B, Chen N, Pei G, Zou C. Preliminary experimental study of a specular and a diffuse surface for daytime radiative cooling. Sol Energy Mater Sol Cells 2019;191:290–6.

[46] Zhao B, Hu M, Ao X, Chen N, Pei G. Radiative cooling: a review of fundamentals, materials, applications, and prospects. Appl Energy 2019;236:489–513.

[47] Bijarniya JP, Sarkar J, Maiti P. Environmental effect on the performance of passive daytime photonic radiative cooling and building energy-saving potential. J Clean Prod 2020;274:123119.

[48] Yang L, Feng C, Bai L, Bao R, Liu Z, Yang M, et al. Flexible shape-stabilized phase change materials with passive radiative cooling capability for thermal management. Chem Eng J 2021;425:131466.

[49] Pech-May NW, Retsch M. Tunable daytime passive radiative cooling based on a broadband angle selective low-pass filter. Nanoscale Adv 2019;2 (1):249–55.

[50] Huang ZF, Ruan XL. Nanoparticle embedded double-layer coating for daytime radiative cooling. Int J Heat Mass Transf 2017;104:890–6.

[51] Li X, Peoples J, Yao P, Ruan X. Ultrawhite $BaSO_4$ paints and films for remarkable daytime subambient radiative cooling. ACS Appl Mater Interfaces 2021;13(18):21733–9.

[52] Liu HH, Kang HJ, Jia X, Qiao XS, Qin W, Wu XH. Commercial-like self-cleaning colored ZrO_2-based bilayer coating for remarkable daytime sub-ambient radiative cooling. Adv Mater Technol-Us 2022;7(10):2101583.

[53] Xiang B, Zhang R, Luo YL, Zhang S, Xu L, Min HH, et al. 3D porous polymer film with designed pore architecture and auto-deposited SiO_2 for highly efficient passive radiative cooling. Nano Energy 2021;81:105600.

[54] Ao X, Liu J, Hu M, Zhao B, Pei G. A rigid spectral selective cover for integrated solar heating and radiative sky cooling system. Sol Energy Mater Sol Cells 2021;230:111270.

[55] Wang S, Wang Y, Zou Y, Chen G, Ouyang J, Jia D, et al. Biologically inspired scalable-manufactured dual-layer coating with a hierarchical micropattern

for highly efficient passive radiative cooling and robust superhydrophobicity. ACS Appl Mater Interfaces 2021;13(18):21888–97.

[56] Zhao B, Yue X, Tian Q, Qiu F, Zhang T. Controllable fabrication of ZnO nanorods@cellulose membrane with self-cleaning and passive radiative cooling properties for building energy-saving applications. Cellul 2022;29(3):1981–92.

[57] Tu Y, Tan X, Qi G, Yang X, Ouyang X, Yan W, et al. Transparent, anti-corrosion and high broadband emission coating for zero energy consumption cooling technology. Mat Today Phys 2023;34:101070.

[58] Naghshine BB, Saboonchi A. Optimized thin film coatings for passive radiative cooling applications. Opt Commun 2018;410:416–23.

[59] Wang X, Liu X, Li Z, Zhang H, Yang Z, Zhou H, et al. Scalable flexible hybrid membranes with photonic structures for daytime radiative cooling. Adv Funct Mater 2020;30(5):1907562.

[60] Wu W, Lin S, Wei M, Huang J, Xu H, Lu Y, et al. Flexible passive radiative cooling inspired by Saharan silver ants. Sol Energy Mater Sol Cells 2020;210:110512.

[61] Wang T, Wu Y, Shi L, Hu X, Chen M, Wu L. A structural polymer for highly efficient all-day passive radiative cooling. Nat Commun 2021;12(1):365.

[62] Zhu Y, Luo H, Yang C, Qin B, Ghosh P, Kaur S, et al. Color-preserving passive radiative cooling for an actively temperature-regulated enclosure. Light Sci Appl 2022;11(1):122.

[63] Qi G, Tan X, Tu Y, Yang X, Qiao Y, Wang Y, et al. Ordered-porous-array polymethyl methacrylate films for radiative cooling. ACS Appl Mater Interfaces 2022;14(27):31277–84.

[64] Zhang Y, Tan X, Qi G, Yang X, Hu D, Fyffe P, et al. Effective radiative cooling with ZrO_2/PDMS reflective coating. Sol Energy Mater Sol Cells 2021;229:111129.

[65] Nie S, Tan X, Li X, Wei K, Xiao T, Jiang L, et al. Facile and environmentally-friendly fabrication of robust composite film with superhydrophobicity and radiative cooling property. Compos Sci Technol 2022;230:109750.

[66] Yu Z, Yao Y, Yao J, Zhang L, Chen Z, Gao Y, et al. Transparent wood containing Cs_xWO_3 nanoparticles for heat-shielding window applications. J Mater Chem A Mater Energy Sustain 2017;5(13):6019–24.

[67] Qiu Z, Xiao ZF, Gao LK, Li J, Wang HG, Wang YG, et al. Transparent wood bearing a shielding effect to infrared heat and ultraviolet via incorporation of modified antimony-doped tin oxide nanoparticles. Compos Sci Technol 2019;172:43–8.

[68] Hu X, Zhang YB, Zhang J, Yang HY, Wang FM, Fei B, et al. Sonochemically-coated transparent wood with ZnO: passive radiative cooling materials for energy saving applications. Renew Energy 2022;193:398–406.

[69] Wang S, Jiang T, Meng Y, Yang R, Tan G, Long Y. Scalable thermochromic smart windows with passive radiative cooling regulation. Science 2021;374(6574):1501–4.

[70] Yue Q, Zhang L, He CY, Liu BH, Wang WM, Lu ZW, et al. Polymer composites with hierarchical architecture and dielectric particles for efficient daytime subambient radiative cooling. J Mater Chem A Mater Energy Sustain 2023;11(6):3126–35.

[71] Liu CH, Ay C, Kan JC, Lee MT. The effect of radiative cooling on reducing the temperature of greenhouses. Materials 2018;11(7):1166.

[72] Hsu PC, Song AY, Catrysse PB, Liu C, Peng Y, Xie J, et al. Radiative human body cooling by nanoporous polyethylene textile. Science 2016;353(6303):1019–23.

[73] Cui L, Huang C, Xia H, Qiu Y, Ni Q. Transparent passive-cooling composite films for indoor and outdoor spaces. Compos Commun 2021;24:100611.

[74] Mutwiwa UN, Tantau HJ, von Elsner B, Max JF. Effects of a near infrared-reflecting greenhouse roof cover on the microclimate and production of tomato in the tropics. Agric Eng Int CIGR J 2017;19(3):709.

[75] Chen WL, Shen CJ. Near-infrared reflective diffusion coating is beneficial for asparagus summer production in a simple plastic greenhouse. HortSci 2022;57(2):257–64.

[76] Chen WL, Shen CJ, Hsu HS, Chien CS. Evaluation on near infrared-reflective diffuse coating for muskmelon production in simple plastic greenhouse during summer season. Acta Hortic 2022;1353:279–92.

[77] Alsadon A, Al-Helal I, Ibrahim A, Abdel-Ghany A, Al-Zaharani S, Ashour T. The effects of plastic greenhouse covering on cucumber (Cucumis sativus L.) growth. Ecol Eng 2016;87:305–12.

[78] de Visser PHB, Buck-Sorlin GH, van der Heijden GWAM. Optimizing illumination in the greenhouse using a 3D model of tomato and a ray tracer. Front Plant Sci 2014;5:48.

[79] Shin J, Hwang I, Kim D, Moon T, Kim J, Kang WH, et al. Evaluation of the light profile and carbon assimilation of tomato plants in greenhouses with respect to film diffuseness and regional solar radiation using ray-tracing simulation. Agric Meteorol 2021;296:108219.

[80] Cappa CD, Wilson KR, Messer BM, Saykally RJ, Cohen RC. Optical cavity resonances in water micro-droplets: Implications for shortwave cloud forcing. Geophys Res Lett 2004;31(10):L10205.

[81] Bhattacharjee S. DLS and zeta potential - what they are and what they are not? J Control Release 2016;235:337–51.

[82] Yeh SL. A study of light scattered by surface-relief holographic diffusers. Opt Commun 2006;264(1):1–8.

[83] Colombo A, Tassone F, Santolini F, Contiello N, Gambirasio A, Simonutti R. Nanoparticle-doped large area PMMA plates with controlled optical diffusion. J Mater Chem C Mater Opt Electron Devices 2013;1(16):2927–34.

[84] Suthabanditpong W, Tani M, Takai C, Fuji M, Buntem R, Shirai T. Facile fabrication of light diffuser films based on hollow silica nanoparticles as fillers. Adv Powder Technol 2016;27(2):454–60.

[85] Park HG, Khang DY. High-performance light diffuser films by hierarchical buckling-based surface texturing combined with internal pores generated from physical gelation induced phase separation of binary polymer solution. Polymer 2016;99:1–6.

[86] Wu G, Guo S, Yin Y, Sun G, Zhong YJ, You B. Hollow microspheres of SiO_2/PMMA nanocomposites: preparation and their application in light diffusing films. J Inorg Organomet Polym 2018;28(6):2701–13.

[87] Magrini T, Bouville F, Lauria A, Le Ferrand H, Niebel TP, Studart AR. Transparent and tough bulk composites inspired by nacre. Nat Commun 2019;10:2794.

[88] Bavi EP, Jouybari SN, Mousavi F. A rapid method for producing highly diffuse reflective white paint as the back surface reflector in dye-sensitized solar cell. Opt Mater 2022;131:112647.

[89] Luo SS, Xue J, Xiong Y, Shen JB, Guo SY. Light-scattering properties of linear low density polyethylene/polystyrene films fabricated through layer-multiplying technology. J Appl Polym Sci 2016;133(33):43826.

[90] Guo S, Zhou S, Li H, You B. Light diffusing films fabricated by strawberry-like PMMA/SiO_2 composite microspheres for LED application. J Colloid Interface Sci 2015;448:123–9.

[91] Bahramian A. Poly(ethylene terephthalate)-based nanocomposite films as greenhouse covering material: Environmental sustainability, mechanical durability, and thermal stability. J Appl Polym Sci 2021;138(10):49991.

[92] Raj B, Sankar UK, Siddaramaiah. Low density polyethylene/starch blend films for food packaging applications. Adv Polym Technol 2004;23(1):32–45.

[93] Zhou L, Ma H, Han C, Hu W, Zhang S, Zhang L, et al. A novel light diffuser based on the combined morphology of polymer networks and polymer balls in a polymer dispersed liquid crystals film. RSC Adv 2018;8(39):21690–8.

[94] Liang CJ, Liu SM, Wirasaputra A, Zhao JQ, Fu Y. Light diffusing and flame-retardant polycarbonate modified by highly efficient and multifunctional organosilica microspheres. J Therm Anal Calorim 2021;146(6):2423–33.

[95] ASTM D1003-13: standard test method for haze and luminous transmittance of transparent plastics. Conshohocken, PA: ASTM International West Conshohocken; 2013.

[96] Busato S, Kremer D, Perevedentsev A. Imaging-based metrics drawn from visual perception of haze and clarity of materials. I. method, analysis, and distance-dependent transparency. Macromol Mater Eng 2021;306(5):2100045.

[97] Jacucci G, Schertel L, Zhang Y, Yang H, Vignolini S. Light management with natural materials: from whiteness to transparency. Adv Mater 2021;33(28):e2001215.

[98] Chen J, Xu F, Tan D, Shen Z, Zhang L, Ai Q. A control method for agricultural greenhouses heating based on computational fluid dynamics and energy prediction model. Appl Energy 2015;141:106–18.

[99] Baxevanou C, Fidaros D, Bartzanas T, Kittas C. Yearly numerical evaluation of greenhouse cover materials. Comput Electron Agric 2018;149:54–70.

[100] Saberian A, Sajadiye SM. The effect of dynamic solar heat load on the greenhouse microclimate using CFD simulation. Renew Energy 2019;138:722–37.

[101] Cabrera FJ, Baille A, Lopez JC, Gonzalez-Real MM, Perez-Parra J. Effects of cover diffusive properties on the components of greenhouse solar radiation. Biosyst Eng 2009;103(3):344–56.

[102] Hemming S, Mohammadkhani V, van Ruijven J. Material technology of diffuse greenhouse covering materials—influence on light transmission, light scattering and light spectrum. In: International Symposium on New Technologies for Environment Control, Energy-Saving and Crop Production in Greenhouse and Plant Factory – Greensys; 2013 Oct 6–11; Jeju, SOUTH KOREA. Korbeek-Lo: ISHS; 2014. p. 883–95.

[103] Riga P, Benedicto L, Gil-Izquierdo Á, Collado-González J, Ferreres F, Medina S. Diffuse light affects the contents of vitamin C, phenolic compounds and free amino acids in lettuce plants. Food Chem 2019;272:227–34.

[104] Zheng L, Zhang Q, Zheng K, Zhao S, Wang P, Cheng J, et al. Effects of diffuse light on microclimate of solar greenhouse, and photosynthesis and yield of greenhouse-grown tomatoes. HortSci 2020;55(10):1605–13.

[105] Rasheed A, Kwak CS, Kim HT, Lee HW. Building energy an simulation model for analyzing energy saving options of multi-span greenhouses. Appl Sci 2020;10(19):6884.

[106] Yu N, Chen C, Mahkamov K, Han F, Zhao C, Lin J, et al. Selection of a phase change material and its thickness for application in walls of buildings for solar-assisted steam curing of precast concrete. Renew Energy 2020;150:808–20.

[107] Zhang SH, Guo Y, Zhao HJ, Wang Y, Chow D, Fang Y. Methodologies of control strategies for improving energy efficiency in agricultural greenhouses. J Clean Prod 2020;274:122695.

[108] Achour Y, Ouammi A, Zejli D. Technological progresses in modern sustainable greenhouses cultivation as the path towards precision agriculture. Renew Sustain Energy Rev 2021;147:111251.

[109] Esmaeli H, Roshandel R. Optimal design for solar greenhouses based on climate conditions. Renew Energy 2020;145:1255–65.

[110] Yadav AS, Agrawal A, Sharma A, Gupta A. Revisiting the effect of ribs on performance of solar air heater using CFD approach. Mater Today Proc 2022;63:240–52.

[111] Kumar T, Jha U, Raj Y, Kumar A. Simulation modeling of a greenhouse integrated with earth-air heat exchanger system. In: Kumar A, Kumar M, Subramanian KA, Lim H, editors. Recent Advances in Manufacturing and Thermal Engineering. Singapore: Springer Nature Singapore; 2023.

[112] Yu G, Zhang S, Li S, Zhang M, Benli H, Wang Y. Numerical investigation for effects of natural light and ventilation on 3D tomato body heat distribution in a Venlo greenhouse. Inf Process Agric 2022 [In press].

[113] Krishna N. History of controlled environment horticulture: greenhouses. HortSci 2022;57(2):239–46.

[114] Ministry of Agriculture and Rural Affair of the People's Republic of China. Opinions of Ministry of Agriculture and Rural Affair of the People's Republic of China on accelerating the development of facility planting. Report. Beijing: Ministry of Agriculture and Rural Affair of the People's Republic of China; 2020. Chinese.

[115] Ani A, Gopalakirishnan P. Automated hydroponic drip irrigation using big data. In: 2020 Second International Conference on Inventive Research in Computing Applications (ICIRCA); 2020 Jul 15–17; Coimbatore, India; Piscataway: IEEE; 2020.

[116] Mamatha Bai BG, Rashmi NS. Data mining techniques in the agricultural sector. In: Shetty NR, Patnaik LM, Nagaraj HC, Hamsavath PN, Nalini N, editors. Emerging Research in Computing, Information, Communication and Applications. Singapore: Springer Singapore; 2021.

[117] Kamath P, Patil P, Shrilatha S, Sushma SS. Crop yield forecasting using data mining. Global Transitions Proceedings 2021;2(2):402–7.