Advanced Optical Materials for Sunlight Control in Greenhouses

Gilles H. Timmermans, Silke Hemming, Esteban Baeza, Evelien A. J. van Thoor, Albert P. H. J. Schenning, and Michael G. Debije**

The increasing demand for efficiently growing vegetation in greenhouses requires continual improvement of the control of the growth environment experienced by the plants. The single most important factor in maximizing the crop's growth is the quantity, quality, and geometrical distribution of radiation intercepted at every moment. Few available greenhouse coverings are capable of responding to changes in sunlight conditions by themselves, limiting the grower's control: they must use additional technologies, including screens, artificial lighting, heating, and cooling. This review considers existing efforts in providing adaptable greenhouse covering systems and advanced optical materials for controlling the color, intensity, and/or distribution of sunlight transmitted into greenhouse-like structures by describing existing static materials and their responsive equivalents. This work also offers speculation on potential applications of other light-control elements, mostly designed for use in the urban environment that can be adapted for greenhouse use in the future.

1. Introduction

About 38% of dry land area worldwide is dedicated to agriculture, which is close to the maximum suitable for this purpose.[1,2] Greenhouses and similar constructions are designed to help meet growing food demands by increasing the production on existing land[3] and allowing use of areas otherwise unsuitable for agriculture.[4] The total global area for growth of herbs and vegetables in greenhouses (permanent structures) covered with glass and plastic is about 500 000 hectares, 40 000 hectares of which are glass.[5] The average production volume of vegetables per greenhouse increased about 36% between 2000 and 2017. The largest single crop, tomatoes, showed a 75% increase, while zucchini production was more than doubled (138%), and strawberries were even greater at 177% (see **Figure 1**).[6]

The primary roles of greenhouses are to protect crops from harmful weather phenomena (such as hail, snow, and rainstorms), birds, pest insects, help maintain stable temperatures to improve quantity and quality of the crops,[3] and control of solar irradiance, key to plant growth.[7] Solar irradiance consists of several wavelength regimes, with ultraviolet (UV < 400 nm), photosynthetically active radiation (PAR, 400–700 nm), and near infrared (NIR, 700–2500 nm) having the greatest relevance for greenhouses (see **Figure 2**a,[3,8] and Figure 2b[9] for a depiction of light intensity distribution around the globe). To make the growth requirements even more complex, the radiation needs of plants can vary between species, the time of day, or the day of the year, and less than optimum conditions can curtail crop production.[7,10]

UV light plays a key role in the morphology of specific plants and their secondary metabolites,[7] and can influence the behavior of pests,[3,11–14] but also helpful insects and pollinators.[15,16] UV also influences the generation of diseases within greenhouses.[17]

The most important irradiance for photosynthesis is PAR. In high latitude (e.g., Dutch) greenhouses, the availability of PAR light often limits plant growth, the rule of thumb being a ≈1% variation in the available amount of light for a crop results in a ≈0.8% change in crop yield.[18] In these Dutch greenhouses, considerable effort is made to increase the amount of PAR light that enters greenhouses, including regular roof cleaning[19] and applying antireflection (AR) surface treatments,[3,17] while research is done on new surface structures, such as zigzag shaped plastics,[20] new plastic compounds and lighter materials,[21] and using fluorescent materials to convert shorter wavelengths of light into PAR.[22,23]

PAR direction and geometrical distribution can be separated into direct and diffuse components. Direct radiation reaches the earth unimpeded from the sun. However, at overly high intensities, direct radiation is likely to damage crops.[24,25] Diffuse radiation occurs when solar light is scattered before

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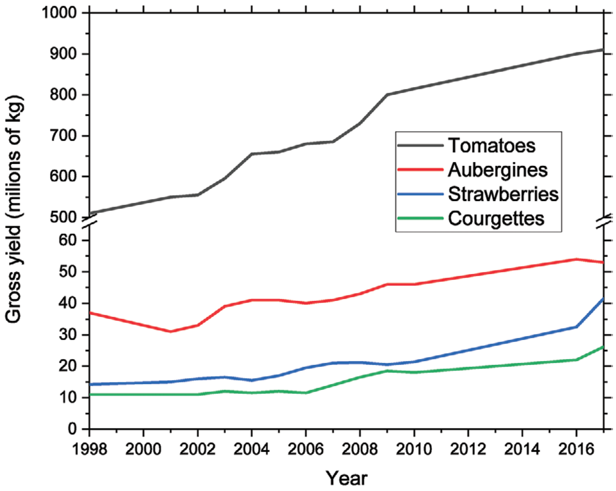

Figure 1. Worldwide greenhouse production 2000–2017 as determined by the Agricultural Census 2017, conducted by Statistics Netherlands (CBS).[6]

encountering the crop, for example by clouds and particles in the atmosphere, or by special scattering greenhouse cover materials. While diffuser materials can reduce the absolute intensity of incident light, they often enhance light penetration deeper into the crop canopy, resulting in better horizontal and vertical light distributions, improving growth and development.[26,27]

NIR, on the other hand, is only ≈40% absorbed by crops, mostly being converted into latent and sensible heat inside the greenhouse. This heating can have positive or negative effects. In cold periods when it is desirable to increase the interior temperature of the greenhouse, NIR heating is an advantage; however, in hot periods when the temperature inside the greenhouse must be artificially reduced, it is a significant disadvantage.[28] As added complication, the requirements of NIR often vary with the seasons and even during the course of a day.[29]

Both glass and most plastics that are used as greenhouse coverings transmit UV, PAR, and NIR to certain extents. Control of light, in directionality, intensity, and color, is vitally important for attaining ideal growth conditions. Many of these growth characteristics depend on plant type, variety, stage of growth, position on the globe, type of greenhouse structure and equipment, and a host of other variables (see Figure 2c)[30].

The control of solar radiation is generally not regulated by the greenhouse structure itself, but only by add-on technologies such as screens, supplementary lighting, heating, cooling, and so forth.[31,32] Because the growth requirements of the plant is constantly changing, it could revolutionize greenhouse growing if the materials making up the greenhouses themselves could directly alter light transmission, direction, or quality in response to these changes. Doing so could increase crop production and profitability, enhancing their nutritional value and appearance.[33,34] In this review, we will consider advanced optical

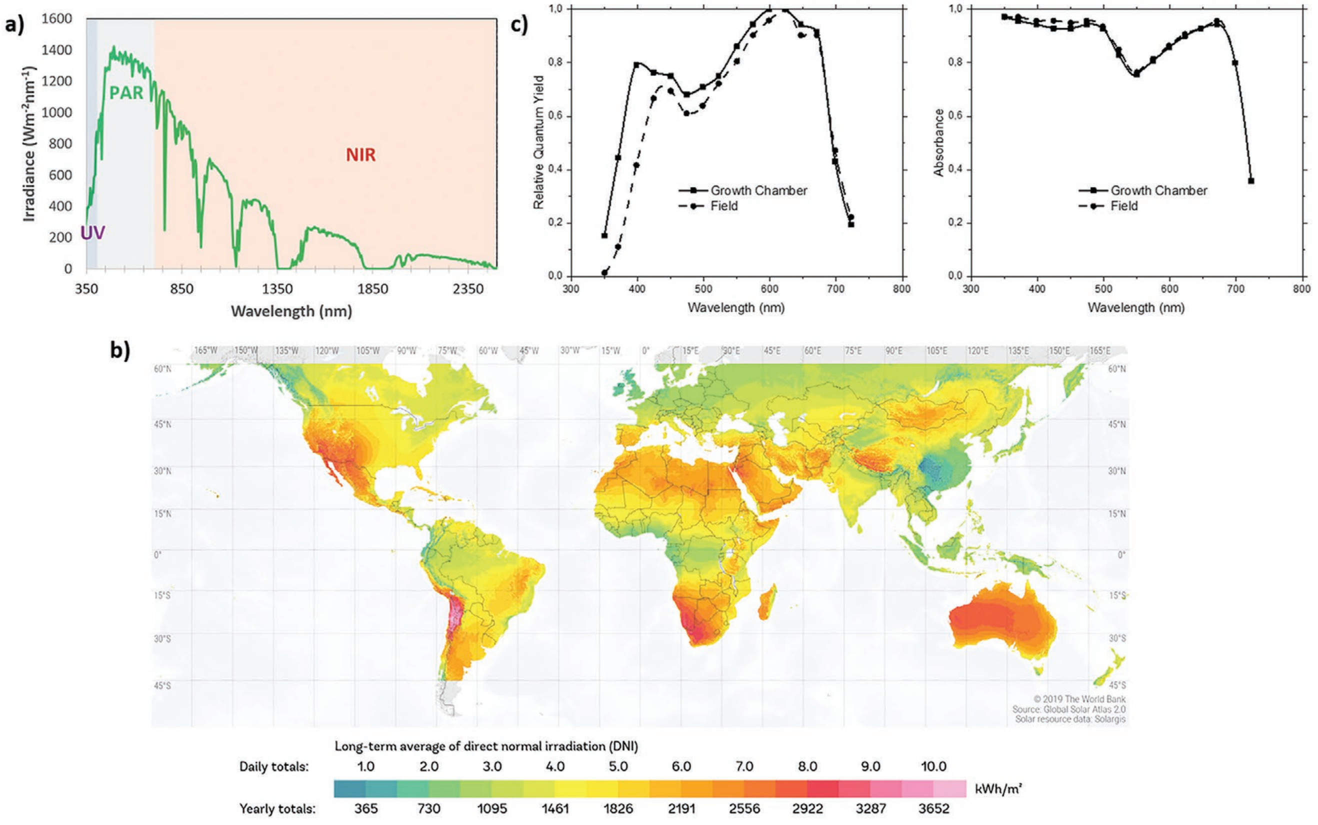

Figure 2. a) Calculated AM1.5 spectrum showing the spectral coverage and relative contributions from ultraviolet (UV), photosynthetically active radiation (PAR), and near infrared (NIR) radiation; b) global direct normal irradiation. Reproduced with permission.[9] Copyright 2019, Solargis; c) data showing the quantum yields (uptake of CO_2 per absorbed photon) and spectral absorbances of leaves averaged for 22 species of plants grown in controlled locales and in the field. Adapted with permission.[30] Copyright 1972, Elsevier.

materials and architectures designed for the control of all important bandwidths of solar radiation. While there are only limited instances of adaptive optical materials currently being integrated in greenhouse structures, we will extrapolate possibilities for new devices based on existing research that could be transferred to greenhouses. This review will focus on manipulation of natural sunlight, and will not discuss the common use of use of artificial lighting such as LEDs to influence plant growth.[7,35]

2. Sunlight Intensity and Distribution Control

The quantity and quality of light are both important elements in plant growth. Too much light may be as damaging as too little light. The distribution of light also plays a key role: diffuse light has shown to improve plant yields by decreasing the chance of plant stress, altering crop morphology, and light interception,[27,36,37] resulting in a particular interest in materials that give rise to diffusion for construction of greenhouses.[27,38] In this section, we will discuss systems designed to control both of these aspects of sunlight.

2.1. Intensity and Distribution Control Via Scattering

Modified light transmission through a greenhouse roof can be achieved by coverings[39–41] or permanent coatings.[17] In warm regions, shading is often required to decrease temperatures. The most common shading methods use temporary coatings that scatter the incoming light, such as simple whitewashes using calcium oxide or calcium carbonate applied to the external roof surfaces before anticipated hot periods, and removed for cooler periods,[42] although there are examples of scattering material being applied directly to plant leaves themselves.[43] While simple, there are potential disadvantages, including premature washing away by rain,[44] spatial heterogeneity,[45] or excessive shading, reducing plant growth by the removal of the PAR.[46,47] Movable shading screens allow for more control of light transmission on a daily basis. However, an interior screen often interferes with ventilation,[48] and exterior screens have other drawbacks (foiling by dust, damage by wind), in spite of the good ventilation performance.[49,50] Only a highly porous, movable internal screen seems to perform better than a whitewash.[51]

Devices that can switch from a transparent to a light scattering state to actively control sunlight intensity might have benefits. Considerable research has already been done on "smart" windows that can switch from a transparent to a light scattering state for use in the built environment. Many different systems are under investigation, including polymer dispersed liquid crystals (PDLCs),[52–54] polymer stabilized liquid crystals (PSLCs),[55] electrodynamic instabilities,[56,57] and other techniques.[58–60] Some switchable PDLC/PSLC windows are already commercially available.[61,62]

PDLCs are made by dispersing liquid crystal (LC) droplets throughout a polymer matrix. Light is scattered due to the refractive index mismatch between the randomly ordered LC and the host polymer matrix. Application of an electrical field aligns the birefringent LC droplets. By aligning the LC, the effective LC refractive index matches the refractive index of the polymer matrix, and a transparent state is attained. The system has maximum transparency for incoming PAR normal to the PDLC, allowing it to be used as an angular discriminating device.[53] For greenhouse applications, this might be adapted to become more or less transparent over the course of a day, as the angle of the sun changes. Most PDLC systems are scattering in the "off" state, but reverse mode PDLCs that are transparent in the "off" state also exist.[54] A variation of PDLCs are PSLCs where the polymer content is greatly reduced which lowers the voltage required for switching between states. These systems are maturing rapidly, with large (40 × 50 cm^2) prototypes (see **Figure 3**) stable for over 100 000 switches being demonstrated.[55] A key research challenge is to extend the photostability of these devices, as UV light is often quite damaging to the LC components. While 5-year guarantees are now offered on some windows,[63,64] these times must be extended to allow widespread adoption in the greenhouse industry.

A technique that could help improve the UV stability of switchable scatterers is the use of electrohydrodynamic instabilities. Electrohydrodynamic instabilities in LCs have been investigated since the 1960s,[65] and may be used to create "smart" windows by doping a nematic liquid crystal with an ionic dye, which upon application of an electrical field generate vortexes in the LC host that scatter the light: see **Figure 4**.[56,57] A main advantage of such a system is that it does not contain any polymer, thus removing the polymerization step and potentially increasing device lifetimes. Such devices have been shown to be capable of switching thousands of times from

Figure 3. a) Prototype of a 40 × 50 cm^2 polymer stabilized liquid crystals (PSLCs) window in the "off" (0 V) and "on" (40 V) states. b) Transmittance of sample windows as a function of applied voltage and switching time. Reproduced with permission.[55] Copyright 2020, Wiley Periodicals.

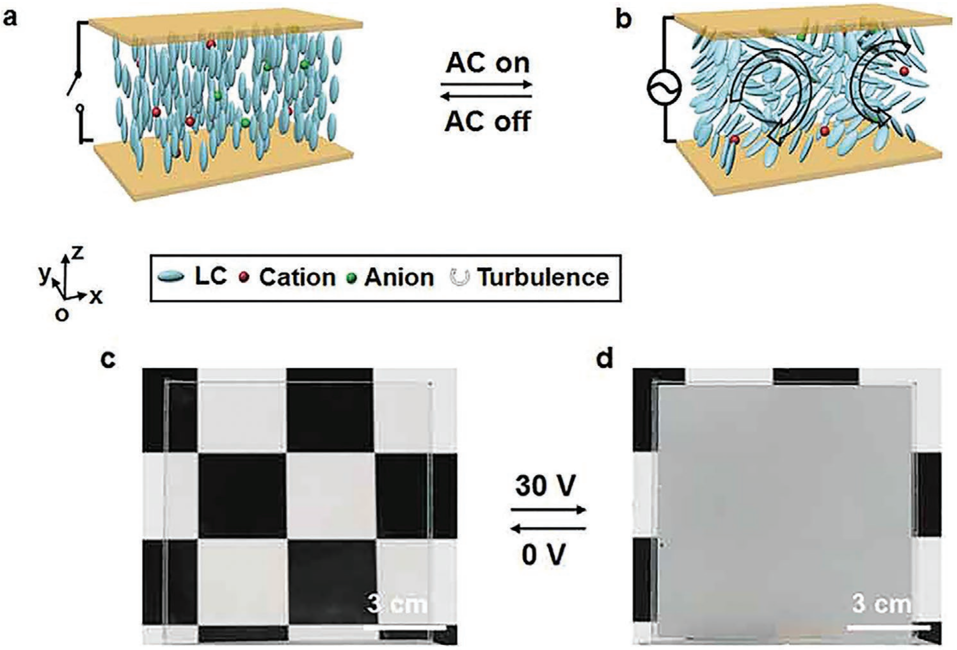

Figure 4. Schematic displaying electrohydrodynamic instability at a) 0 V and b) >0 V AC field. Photographs of the 9 × 9 cm^2 cell at c) 0 V and d) 30 V. Reproduced with permission.[56] Copyright 2019, Taylor & Francis Group.

>95% transmission and almost no scattering to ≈10% transparent with >90% scattering.[56]

Creating roughened surfaces is a common way of inducing light scattering, but this is usually not reversible. However, a "smart" window using randomly dispersed nanowires on the top of an elastomer demonstrated reversible surface deformations, forming a scattering state when a voltage was applied (see **Figure 5**).[58] This system could easily be scaled to large areas as it suitable for roll-to-roll fabrication and uses commercially available materials. Challenges that remain are the high voltages required (>1500 V) and the low transmission in the transparent state (≈60%).

Since most of these scattering systems were originally designed for privacy states for domestic use, the literature only reports decreases in directly transmitted light intensity, and not the amount or distribution of forward scattered light. For greenhouse applications, "hortiscatter" is highly desirable for optimal plant growth. In future, both light diffusion and total light transmission should be reported to be able to evaluate the application of these systems for greenhouses.

2.2. Intensity (Only) Control

Systems that can switch from completely transparent to completely opaque states may control both light availability and regulate temperatures inside the greenhouse.[66] Generally, a higher transmission in the (hemispherical) PAR light is desired for crop photosynthesis, but there are exceptions: shade-loving plants, such as ornamental pot plants, must be protected against higher light intensities. Other crops, such as chrysanthemum, are sensitive to the day length. In these crops, blackout screens are used to shorten naturally long days, and block all light to control flowering.[67,68] For switchable blackout screens, transition metal oxides,[69] conjugated polymers,[70] Prussian blue,[71] and dichroic dye[72] based systems have received the most attention. Mechanical solutions are also encountered, such as switchable blinds with absorbers on one face and reflectors on the other.[73]

Recently, the movement of magnetic nanoparticles to create a squid-inspired "smart" window has been proposed.[74] In this device, an array of pyramidal voids is created in a transparent polymer. These voids are filled with a refractive index matching fluid containing magnetic nanoparticles. By applying a magnetic field, the nanoparticles move to the top of the pyramidal voids and become concentrated, significantly increasing the total transparency of the system (see **Figure 6**). An advantage of this device is its simplicity, which could translate into good durability. The main disadvantages are the requirements of a switchable magnetic field, and the concentrated dark regions present even in the transparent state. The research showed decrease of the dark area by replacing the pyramidal structures with hopper-like structures.

Another study used the phase change of VO_2, which converts from an effective insulator into a metal upon heating. When coated on a glass fiber cloth, the VO_2 can be used as a negative feedback material:[75] at low temperatures, the coated glass releases heat, but when the temperature is high, the VO_2 absorbs heat, resulting in a decreased interior temperature. In experiments, with a temperature increase from 30 °C to 40 °C (a desired range for greenhouse applications), the reflection of VO_2 on glass fiber cloth decreased by 22% for the wavelength range of 400–800 nm, meaning more light was absorbed. However, reflection of PAR even in the most transmissive case is very high, and probably not applicable to an actual greenhouse.

Another option that does not require a continuous power supply is to make use of holographic optical elements suggested for use in buildings for light control.[59] Applied to a greenhouse, the transmission of light would change throughout the day as

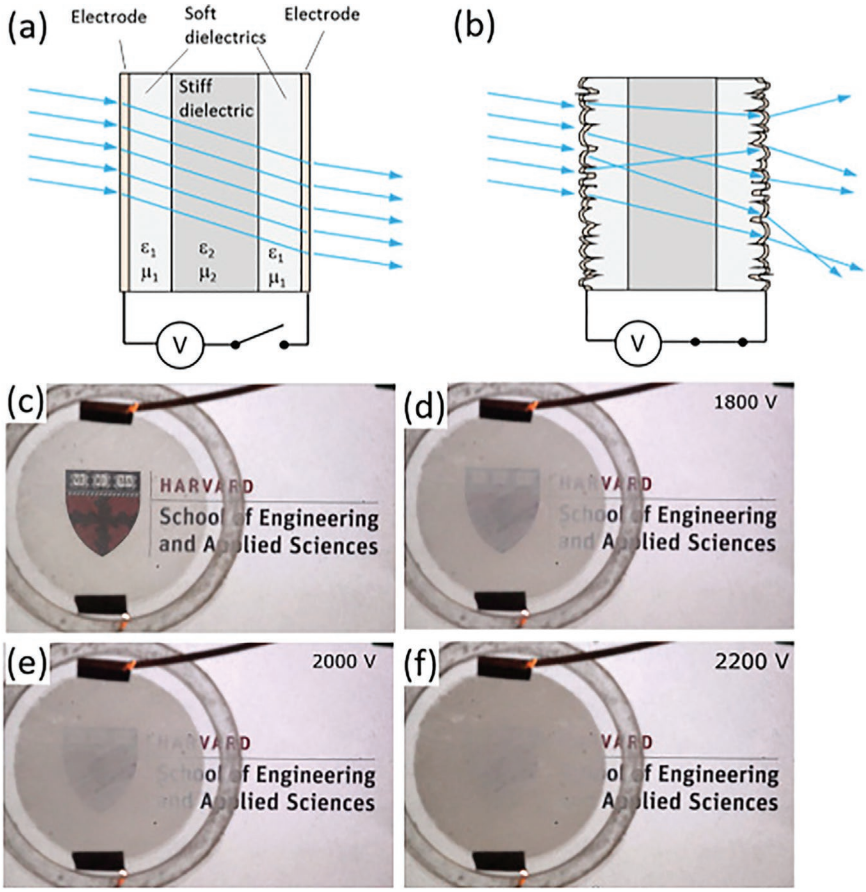

Figure 5. a) Schematic of the nanowire-topped device, which in the "off" state has a smooth surface. b) Schematic of the device in the "on" state where the randomly dispersed electrodes deform the surface causing the incoming light to scatter. c–f) The increase in scattering as the voltage is increased from 0 V to 2200 V. Reproduced with permission.[58] Copyright 2016, Optical Society of America.

the windows would be angularly dependent, so one could conceivably tune the light distribution changes to occur for specific solar positions, presumably when the incident intensity would be highest. By accounting for the position of the sun throughout the year, the window could be designed to block more light in summer than in winter. These systems are relatively simple, so cost should be low but cannot be modified after installation to adapt to different lighting needs for different plants.

3. Near Infrared Control

Temperature plays an important role in most crop development processes. Optimal growth temperatures usually range between 15 °C and 30 °C.[76] Growth, yield, and quality of most greenhouse crops will be affected whenever the temperature is below 12 °C or above 30 °C.[77] During summer months and in warmer climates, the application of (permanent) NIR selective filters is considered an advantage:[78,79] the energy demand for cooling can be reduced while PAR light is unimpeded, as PAR is the driving force for crop photosynthesis, growth, and development.[18,80] There has been a great deal of research demonstrating blocking NIR in greenhouses is desired during warm periods but not during cold periods,[81,82] with many different materials investigated, including plastic films or coated glass for greenhouses covers,[83–85] movable screens,[86–88] and NIR-filtering temporary coatings.[89,90] However, the reduction of energy required for cooling is often less than could be expected, as the crops themselves already have a high reflectivity for NIR radiation (about 50%), so that NIR radiation transmitted by partially reflective NIR greenhouse coverings or screens will end up being partially trapped within the greenhouse between two reflective surfaces (the roof covering and crop), suggesting 100% NIR reflectors are greatly preferred.[86]

Adaptive coverings responding to seasonal energy demands could be important, especially in unheated greenhouses.[91] Solar light incident on greenhouses changes hourly in incidence angle, intensity, and spectral quality. To better control the ingress of NIR radiation, it would be an advantage to have materials that can respond to these changing conditions, becoming more transparent when more light is needed, but less transparent when it is desirable to reject heat entering the growing space.[34]

Mobile Fresnel lenses are employed in controlling both PAR and NIR,[82,92] and switchable shutters[93] are used to control temperature in greenhouses. Such systems are especially effective in warm climates when combined with ventilation;[94] however, these technologies can be complex and are not yet introduced commercially on a larger scale.

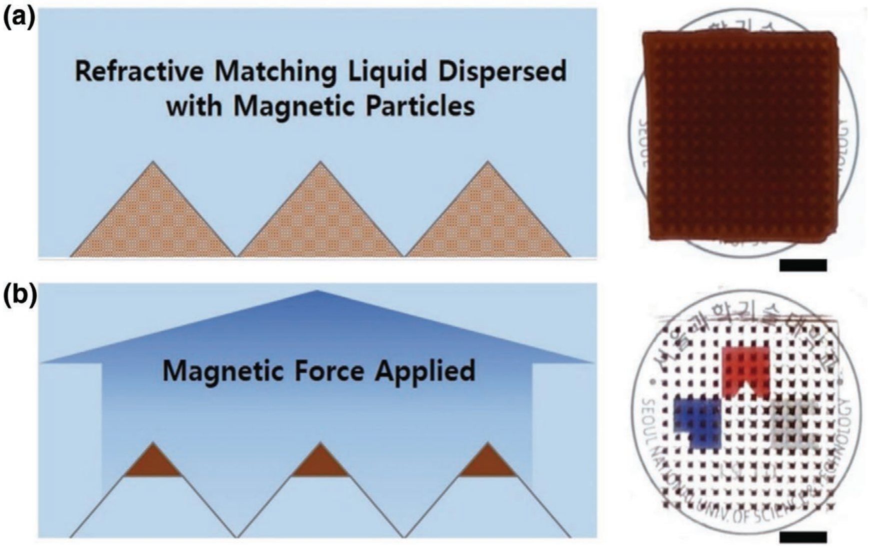

Figure 6. a) Magnetic particles dispersed inside pyramidal voids filled with a refractive index matching liquid causing a colored state. b) An applied magnetic field concentrates the particles at the top of the pyramidal voids creating a mostly transparent state. Reproduced with permission.[74] Copyright 2019, Wiley-VCH.

Recently, research into using advanced optical materials for control of infrared light while retaining high transmission in the visible light has begun.[95] A promising class of materials for light control are nematic LCs doped with a chiral guest, forming a chiral-nematic mesophase, commonly referred to as a cholesteric liquid crystal (CLC). CLCs reflect specific wavelengths of light, while remaining almost completely transparent to other wavelengths. The wavelength reflected may be easily tuned by changing the amount of chiral dopant added to the host LC. CLCs selectively reflect only one circular polarization of incident light matching the “handedness” of the helical structure of the CLC: that is, a right-handed CLC film can reflect a specific bandwidth of right-circularly polarized light. Thus, the CLC can reflect 50% of incident sunlight, given solar radiation is equally distributed between right- and left-circular polarizations.[96] It is possible to make 100% CLC reflectors by layering individual right- and left-handed CLCs, using two like-handed CLCs separated by a halfwave plate, or other techniques.[97,98] However, intriguing research suggests plants are sensitive to the polarization of sunlight: for example, lentils and peas appeared to grow more swiftly under left-handed circularly polarized light;[99] perhaps a single layer of CLC could be effective at controlling incident sunlight without affecting the growth of the plants. Many CLC-based “smart” window architectures feature an additional “hazy” state where the LCs have lost their alignment and scatter most of the incoming light.[100–103] Usually this is presented as an intermediate “privacy” state between the reflective and transparent states, but it could potentially be of further benefit to greenhouses in addition to the IR reflecting state. While CLC systems have shown good switching properties and the wavelength that need to be reflected can be easily controlled, they have not yet been proven to be stable enough for long-term continual outdoor exposure.

Normally, the bandwidth of a cholesteric reflector is too narrow to be of much use as a greenhouse heat control element (≈100 nm in the NIR). Broadening the CLC reflection band (to > 500 nm) may be attained using diffusion of mono- and di-acrylates to form a pitch gradient in the depth of a CLC,[103] or associating two layers of polymer-stabilized CLCs, labeled PSCLCs.[104] In the former case, by mixing photoreactive and non-reactive LC species, it was possible of making an electrically switchable broadband reflector that could have a significant impact on the infrared energy passing through the window (see **Figure** 7a).[103] In the latter case, two individual reflective layers are produced independently and brought into contact, allowing them to diffuse together to create the broadened reflector. This latter system also demonstrated an intermediate, scattering state, which could also be used in light management for greenhouses (Figure 7b).[104] The potential needed to switch these two reflecting windows was somewhat high, over 150 V each, and would need to be lowered for practical application.

Electrically broadened reflection bands of over 1000 nm were demonstrated in CLC systems employing ethylene glycol twin diacrylate cross-linkers using a nematic LC host with negative dielectric anisotropy (see **Figure** 8a).[105] Even more extended reflection bands are possible by exploiting the phase transition between smectic and nematic phases, leading to reflection spectra thousands of nanometers wide, see Figure 8b, increasing the potential heat reduction:[106] however, unlike the previous reflectors, this reflector is not switchable making it only applicable in regions that always have an excess of heat.

In addition to electrically responsive systems, thermally responsive cholesterics have been developed which automatically reflect more of the incident sunlight at higher temperatures. A major advantage is the devices would not need to be connected to the power grid. A downside is that the temperature response is set during production and cannot be changed later and thus needs to be set for the exact crop and climate. Some cholesterics are designed to reflect more light as the temperature increases,[107–110] or have red[111,112] or blue

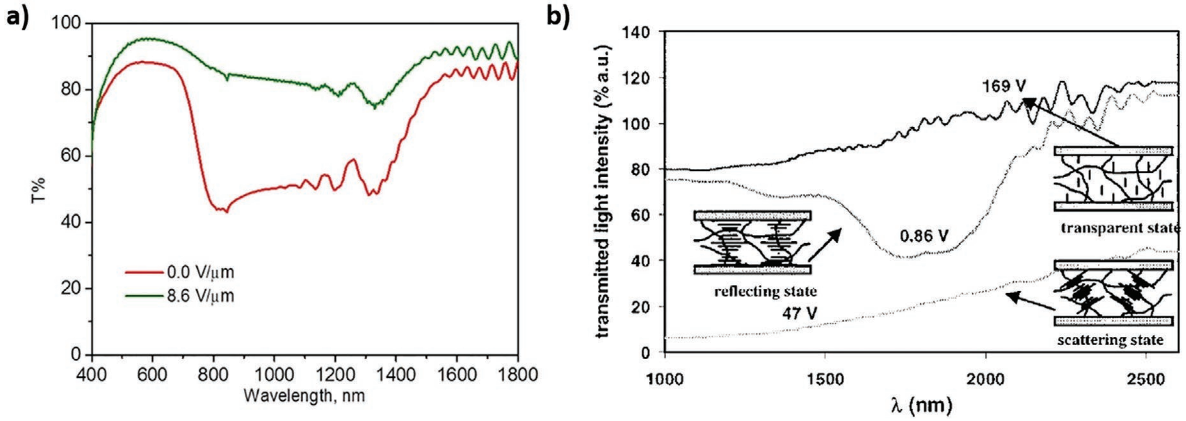

Figure 7. a) Transmission spectrum of reflective and transmissive states of a cholesteric gel at 0 V μm^{-1} and 8.6 V μm^{-1}, respectively. Reproduced with permission.[103] Copyright 2015, Nature Research. b) Intensity of transmitted light intensity versus wavelength for the sandwich cell at three different voltages with drawings of the postulated structures of the polymer stabilized cholesteric liquid crystal (CLC) material. Reproduced with permission.[104] Copyright 2001, American Institute of Physics.

shifts[113–116] of the reflection band:[117,118] shifting the reflection band can be used to control the temperature by designing the shift to coincide with maximal NIR reflection at the desired temperature. The disadvantage of using a red shifting cholesteric is the layer will reflect PAR light at lower temperatures, potentially hindering growing conditions. Blue shifting cholesterics can be tuned to initially reflect at >1400 nm where the sunlight intensity is low, and shift at higher temperatures to the NIR where the sun intensity is higher (see Figure 2a). Thermally responsive systems can also be made into surface coatings,[114–116] something that is difficult to do with electrically responsive systems. Other cholesterics have been developed that trigger on both temperature and humidity, which could be particularly interesting in a greenhouse environment.[119]

The use of temperature-sensitive hydrogels combined with graphene oxide produces windows that switch automatically,

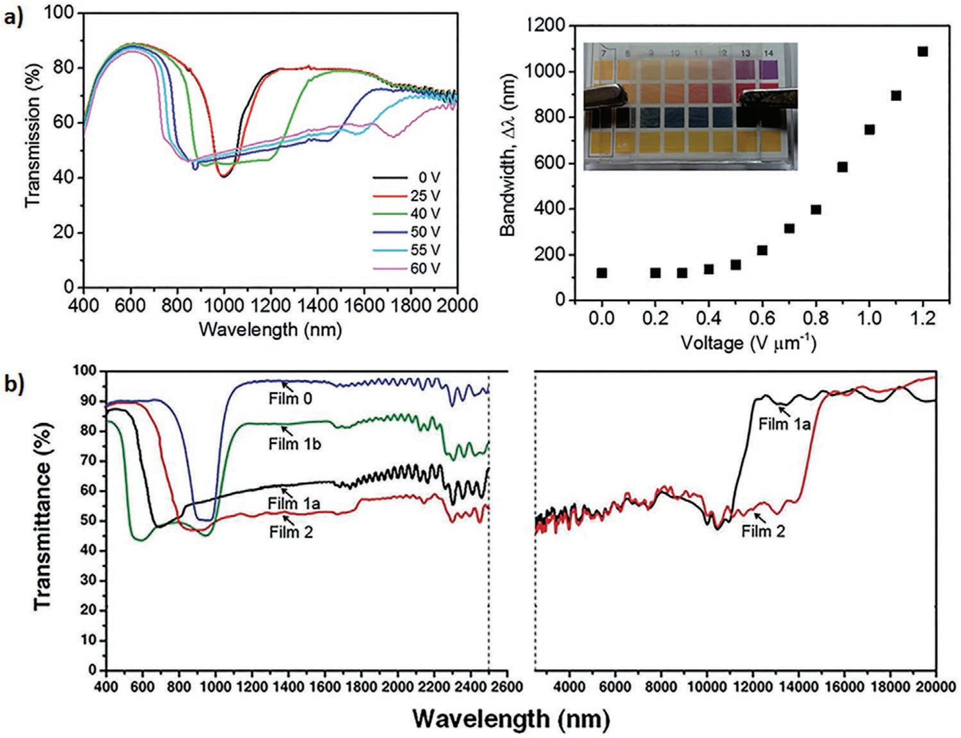

Figure 8. a) (Left) Transmission spectra of CLC mixture in applying 0–60 V; (right) reflection bandwidth as a function of the applied voltage per micron cell thickness with photographs of reflectors demonstrating visible light transparency at 0 V. Reproduced with permission.[105] Copyright 2016, The Royal Society of Chemistry. b) (Left) Schematic showing formation of the short-range ordering (SSO) nanostructures leading to super-broadband reflectors; (right) transmission spectra of films with various internal structures demonstrating the possibility of forming extremely broad reflectors. Reproduced with permission.[106] Copyright 2016, Taylor & Francis.

from full transparency to fully absorbing, in this case at around 28 °C (an appropriate switching temperature).[120] The disadvantage is that, while IR is effectively absorbed, so too is the useful PAR light, often not a desired situation.

4. Color Changes

Within PAR, changes in the color of the light reaching the crops can cause photomorphogenetic responses: these effects are extensively studied.[7,121] Plants behave based on photoreceptors which function as light sensors to analyze the light quality, quantity, duration, and direction.[23,122] Changes in light spectrum influence shoot elongation, formation of side shoots, leaf area and leaf thickness, germination processes, tropisms, flowering induction and development, and color of flowers and leaves.[7] Photoselective films have shown to be able to effect a variety of crops such as delaying the flowering of strawberry plants,[123] and controlling the height (by influencing the red: far red ratio) of poinsettia,[124] antirrhinum,[125,126] chrysanthemum,[126,127] and cherry and peach trees.[128] Many static materials are used to control the color of the light reaching the crops, including colored screens and nets,[8,129–132] reflectors,[133,134] photoselective films,[22,121,124,135,136] fluorescent pigments,[137–139] doped glass,[140,141] and luminescent solar concentrators (LSC).[23,142] These devices often reduce the total amount of PAR, although fluorescent dyes that absorb UV radiation and shifting this to PAR may theoretically increase the effective irradiance.[22,23]

Dynamic control of sunlight color quality is uncommon, although screens and nets can be simply (re)moved, and temporary coatings can be seasonally applied. There do not yet exist systems that change over the course of a day. There have been studies of fluorescence-based LSC architectures (more on this in Section 5) designed to switch between transparent and colored states,[143] or between two different colors, triggered either electrically[144] or spectrally.[145] Either of these latter systems could be used to manipulate the quality of sunlight to better match the changing spectral needs of the plants.

Fluid pumps that circulate liquids through the roofs of greenhouses for cooling purposes have been researched. Additives in the cooling fluid can promote scattering, or the absorption of specific wavelengths of light. By using far red (700–780 nm) absorbing filters (such as $CuSO_4$), the height of "Spears" chrysanthemums could be influenced, with the advantage that the additives to the fluid can be further altered to achieve different purposes.[146] Replacing the absorber with fluorescent dyes could act to alter the spectral content experienced by the plants. A downside of these systems is that they require the installation of a plumbing network and pumps to control the flow, but the specific absorbance could be easily modified. A similar technique for controlling the color of incoming light is by mixing a liquid containing dye together with an unmixable liquid or a gas in a window architecture. An increase in temperature is followed by a corresponding change in density and pressure, causing the liquid containing dye to cover a larger surface of the window, without the need for pumps, thus absorbing more of the incident light (see **Figure 9**).[147]

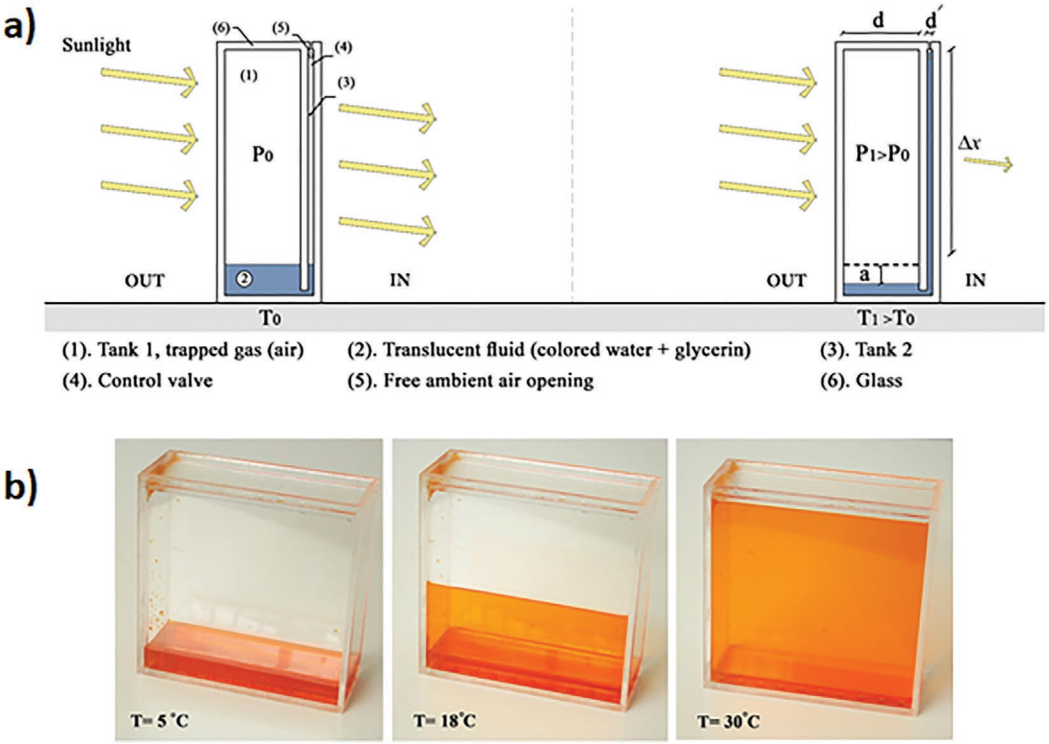

Figure 9. a) Schematic for liquid-based window in the (left) transparent and (right) light blocking states. b) Photographs of the prototype window taken at 5 °C, 18 °C, and 30 °C. Reproduced with permission.[147] Copyright 2016, Elsevier Ltd.

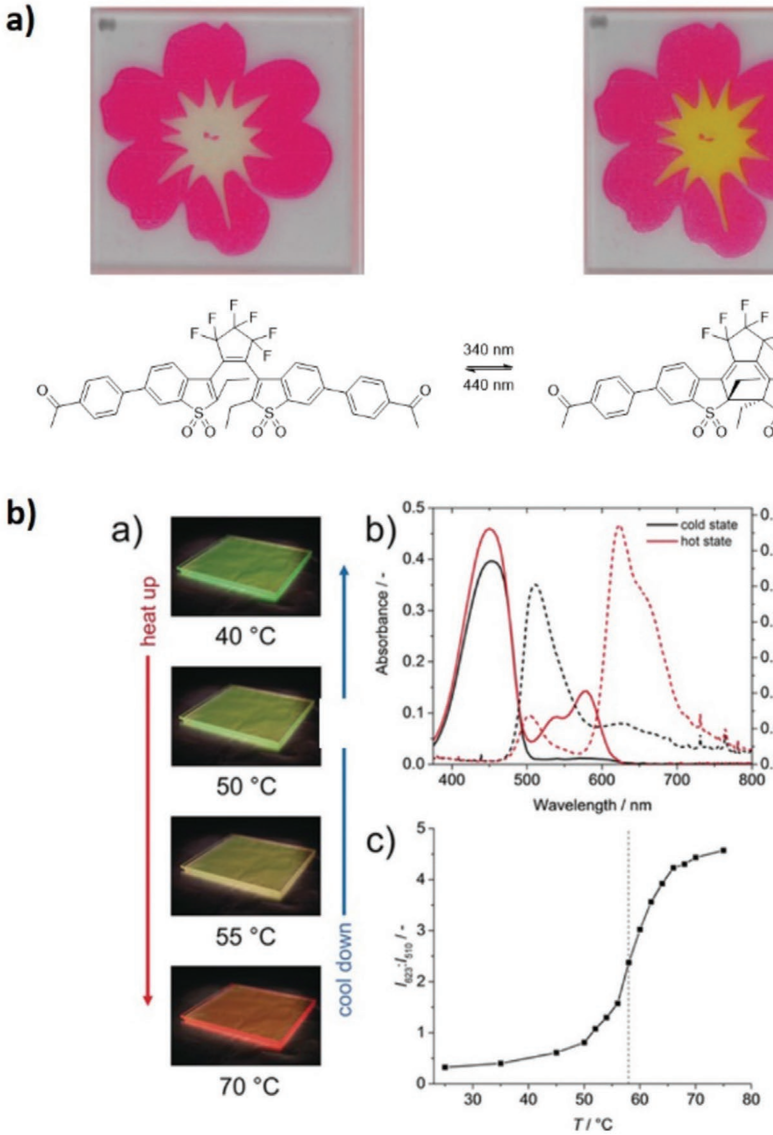

Figure 10. a) Inkjet-printed pattern containing a diarylethene dye (yellow, structure in open and closed states indicated below the photographs) and commercial Lumogen F Red 305 (red) dye before and after switching to the transparent state (2 h of 440 nm light). Reproduced with permission.[148] Copyright 2019, Optical Society of America. b) Photographs of a two-dye cell demonstrating color change as the temperature is increased from 40 °C to 70 °C, absorbance (solid lines) and emission (dotted lines) spectra of a cell filled with the two-dye mixture before (black lines) and after heating to 80 °C (red lines), and ratio between emission intensities at 623 nm and 510 nm: the host LC becomes isotropic at 58 °C (vertical dotted line). Reproduced with permission.[145] Copyright 2017, Wiley-VCH.

By using dyes that respond to external lighting conditions through chemical rearrangement of bonds, UV or PAR can be absorbed during the brightest period of the day, while during periods of decreased brightness the dye can become transparent (see **Figure 10**a). As the embedded dye is fluorescent, the additional emitted light could be directed to the plants to better match the photosynthetic system, or siphoned off to the device edges where photovoltaic (PV) cells can be placed to generate electrical power:[148] more on this topic will be discussed in Section 5.

Finally, temperature responsive dyes have also been studied in a switchable window format. The active fluorescent dye is insoluble in the LC host in the nematic phase at lower temperatures but becomes soluble as the LC transitions to the isotropic phase at higher temperatures and begins to fluoresce. The window thus changes color depending on the external temperature: it could be possible to tune the color change to match the wavelength specific needs of the plant, if desired (Figure 10b).[145]

5. Electricity Generation

Greenhouses can also be used to generate electricity by converting excess light to electricity[10,28,82,149–152] or using the generated power for water/temperature control.[153] Care must be taken when using PV greenhouses that the crop production is not hindered.[154] For this reason PV systems that do not use

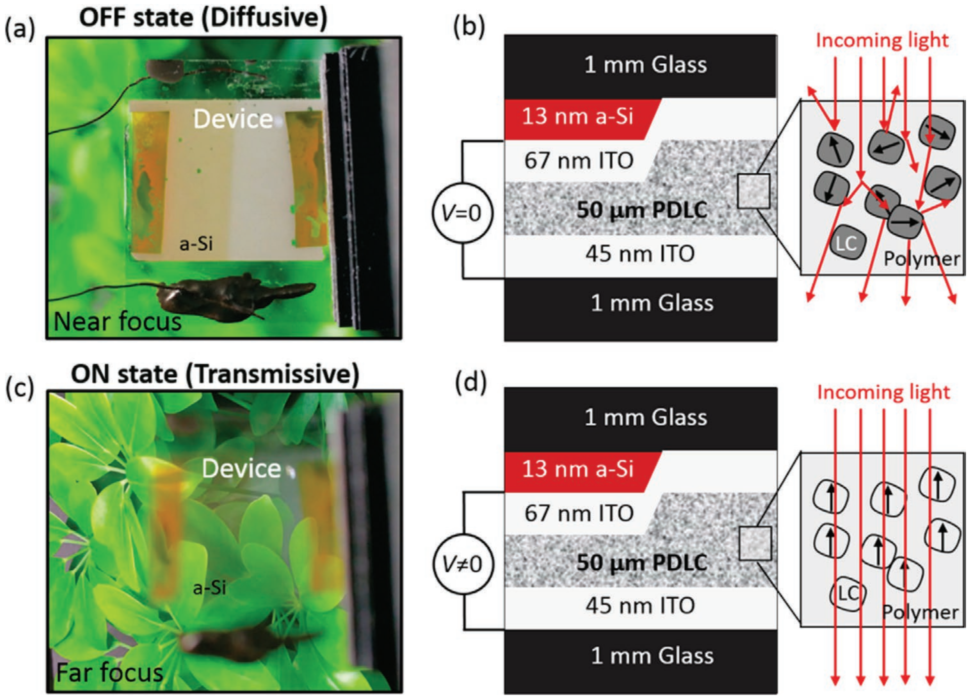

Figure 11. a) Photograph and b) schematic of the combination polymer dispersed liquid crystals (PDLC)/photovoltaic (PV) device in the diffusive state with no applied bias. c) Photograph and d) schematic of the device in the transmissive state at 150 V. Reproduced with permission.[165] Copyright 2016, American Chemical Society.

photons in the PAR regime, or can be switched on and off, are of particular interest.

The top of a greenhouse can be partially covered with PV to generate electricity while ensuring enough light still reaches the crops.[2,155–157] Fresnel lenses can be used to redirect part of the direct sunlight to PV modules, while allowing the diffuse component of the light to pass.[151,158] Semitransparent, wavelength-selective PV cells have been designed that allow some light to be transmitted to the crops below.[159–161] As a decrease of PAR is detrimental to production, NIR absorbing devices that are mostly transparent for PAR are being researched.[162,163] For application in greenhouses the PAR transmission of these systems needs to be significantly increased or they can only find application in regions with very high sunlight intensity.

Devices with switchable transmission could generate electricity in the future.[164,165] A recent example combines the switchable scattering of a normal PDLC, which could help with light distribution, with a PV to make the device self-powering, thus lowering the installation and operating costs (see **Figure 11**).[165]

Another semitransparent concept for generation of electricity in greenhouses is the LSC, which consists of a transparent lightguide (usually plastic or glass) that either contains or is coated with a fluorescent dye. This dye can absorb incident radiation, re-emitting it as down-shifted light, guiding this emission by total internal reflection to the edges of the lightguide. By placing PV cells at these edges, this concentrated light can be converted to electricity.[166,167] LSCs have been industrially deployed in the roofs of greenhouses and shown to be able to generate electricity as well as enhance crop growth via color conversion.[168] As they lower the amount of PAR available for the crops, these systems best deployed in regions with high sun intensities.

Switchable LSC have been described based on dichroic fluorescent dyes embedded in an LC host, whose alignment can be changed on demand using an electrical trigger as shown in **Figure 12**a, resulting in changes of PAR transmission which would greatly increase the ease of use in temperate climates.[143] Recently, switchable LSCs with a third scattering state were fabricated using “supertwisted” LCs which could provide even more functionality for greenhouse applications, as they combine color change, electricity generation, and can provide diffuse light (see Figure 12b).[169]

6. Conclusions

It is obvious the productivity of greenhouses needs to increase as the world’s population and wealth increases, as people demand more, healthier, and better tasting fruits and vegetables without the availability of increased land area to grow these foodstuffs. There is increasing knowledge on the effects that light of various qualities has on plant growth. A number of static materials have been used to address these lighting needs, but most of them are incapable of adjusting lighting conditions on an hourly or even daily basis. It is apparent the study of advanced optical materials specifically for sunlight control for use in greenhouse architectures is in its infancy. In this review, it becomes clear that the research for materials designed for the built environment, with the right adaptation could have a significant impact on future greenhouses. These devices need to be developed and used in larger scale tests to determine their impact on crop growth.

This review shows the challenges for horticulture and the need to develop adaptive optical materials and devices to meet

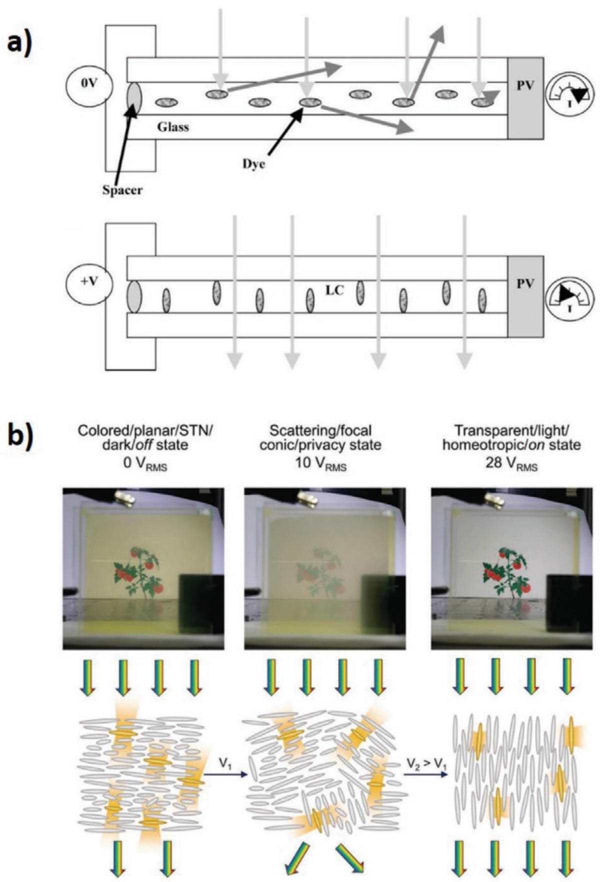

Figure 12. a) Working principle of the luminescent solar concentrators (LSC) switchable window. (Top) At rest, the dye molecules can absorb incoming light and re-emit this light at longer wavelengths, a fraction of which is trapped by total internal reflection and reaches the edge with photovoltaic (PV) attached; (bottom) after electrically switching, the guest dye molecules are reoriented to align parallel to direction of the incoming light; less light is absorbed and allowed to pass through the lightguide into the space beyond. Reproduced with permission.[143] Copyright 2010, Wiley-VCH. b) (Top) Photographs of the dye-doped supertwist liquid crystal (LC) cell at (left) 0 V_{RMS}, (middle) 10 V_{RMS}, and (right) 28 V_{RMS}. (Bottom) Schematic showing the alignment of the LCs, dyes, and the light emission direction. Reproduced with permission.[169] Copyright 2018, Wiley-VCH.

the needs of this growing industry, and to develop simulation tools to estimate the potential impacts of these designs. Perhaps the main roadblock to widespread acceptance of responsive materials, besides the potential additional costs, are the unproven photostabilities of the materials. Many of the material discussed here use polymers, dyes, and liquid crystals that have been known to degrade under UV exposure. For growers to seriously consider using these materials, extended lifetimes are required. Growers are hesitant to employ new coverings that cannot become fully transparent on demand. It is important to note that not only the total hemispherical light transmission is important, as diffusiveness can actually beneficial as long as total light transmission is not affected. Researching solutions for these topics will make up a considerable bulk of forthcoming research in this field.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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