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Review

Alternative Uses of Luminescent Solar Concentrators

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Abstract: Over the last decade, the field of luminescent solar concentrators (LSC) has experienced significant growth, as noted by the increasing number of studies. However, so far, most of the devices developed have only been employed in a simple planar configuration coupled with silicon photovoltaic solar cells. This type of device is essentially a solar window whose main objective is to produce electrical power. However, due to the intrinsic nature of LSC, that is, the ability to absorb, downshift and concentrate the solar radiation that impinges on it, this photonic device can be used in alternative ways. In particular, in this review, we will explore several non-conventional applications in which LSCs are used successfully, including as solar bioreactors for algae development, photo reactors for organic synthesis, and as greenhouses.

Keywords: luminescent solar concentrators; photonic device; photoreactors; controlled environment agriculture

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1. Introduction—The Luminescent Solar Concentrator Device

In its simplest form, a luminescent solar concentrator (LSC) is a fluorophore-containing waveguide with downshifting properties that do not contain any active components able to convert light into electricity [1]. Under irradiation, the fluorophores absorb part of the incident light and re-emit photons at longer wavelengths. The mismatch in refractive indices between the waveguide material and the air causes total internal reflection (TIR) inside the waveguide. For an LSC with a typical refractive index of around 1.5, this means that about 75% of the photons can be internally reflected and guided towards the edges of the waveguide. The properties of the waveguide and of the luminophore, such as its photoluminescent quantum yield and the Stokes shift (i.e., the difference between the spectral position of the maximum of the first absorption band and the maximum of the fluorescence emission), are of fundamental importance to obtain an efficient LSC device [1,2].

The idea of concentrating light using fluorescence and TIR was initially considered in the 50s for collecting light from scintillation counters [3]. However, the concept of using sunlight in combination with LSCs was introduced only in the late 70s with the primary objective of reducing the cost of the electricity produced by silicon photovoltaic (PV) panels [4,5].

In the case of LSC devices used to convert light into electricity, index-matched PV cells are placed at the edges to collect the concentrated photon flux arising from the waveguide (Figure 1) [1,2,6–8]. As the LSC top area exposed to sunlight is larger than the waveguide edges area, the flux of incident radiation onto the PV devices can be significantly increased [9,10]. This, in theory, allows us to reduce the effective area of PVs used to generate an identical amount of electrical power, minimizing the PV material consumption and reducing device cost. In addition, LSCs offer adaptability to the needs of architects for building-integrated photovoltaics (BIPV), such as various colors, shapes, transparencies, lightweight options, and flexibilities, making them an attractive option for high-rise buildings [11].

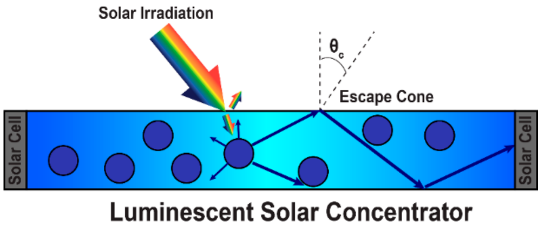

Figure 1. Schematic of a luminescent solar concentrator. Solar cells are usually placed at the device's edges to collect the concentrated light emitted by the luminophores.

During the last decades, most research on LSCs focused mainly on their use as complementary sunlight collectors for traditional PV systems, with considerable effort placed on improving the power output. In particular, the materials used in LSC configurations have rapidly developed. Several luminophores have been developed, such as dyes [7,12–14], hybrid materials [15–17], and semiconducting quantum dots (QDs) [18–24]. Similarly, a large body of work has been dedicated to designing and optimizing the host-polymer waveguides, such as polymeric host matrix systems [25,26].

However, the excellent tunability of the LSC devices allows expanding their use away from their initial concept of electricity generation, realizing a multitude of other applications. In this review, we will explore alternative uses of LSC devices in which the main source of radiation is sunlight, focusing on photochemical reactors for the synthesis of organic molecules, agriculture systems for the growth of plants, and photoreactors for microalgae biomasses (Figure 2).

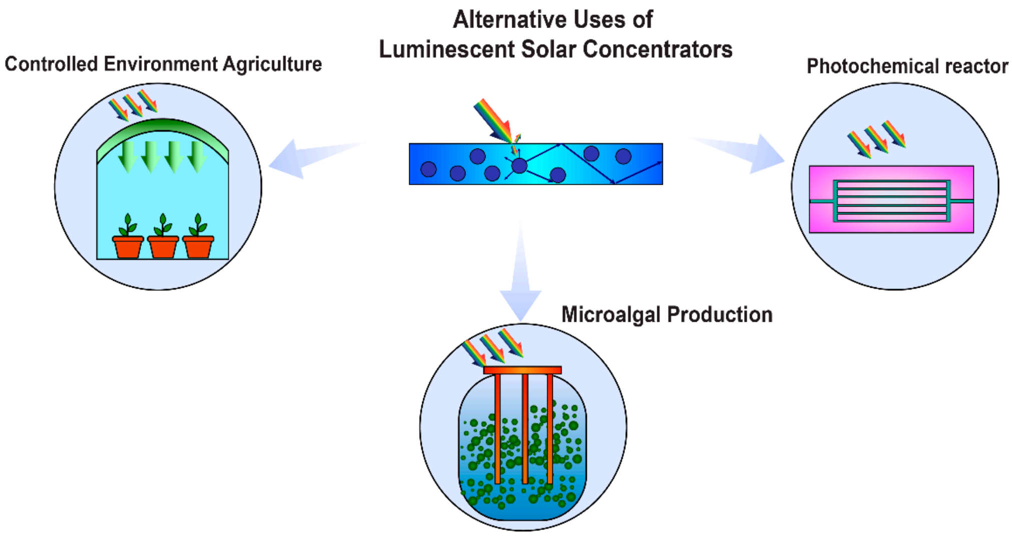

Figure 2. LSCs can be used in various applications, such as agriculture, microalgal production, and photochemical synthesis.

2. LSC Devices as Photochemical Reactors

Since Giacomo Ciamician conceived the notion of photochemistry [27] and particularly during the last few years, photochemical transformations have created a multitude of opportunities for the innovative synthesis of organic products toward more sustainable production of chemicals [28]. In this context, the use of solar radiation as a light source is highly desirable due to its relative abundance. However, the efficiency of photochemical transformations is still fairly low, mainly due to the difficulty of delivering photons to reactants [29].

Two main solar reactors have currently been developed, one in which light is diffuse and the other in which it is concentrated. Non-concentrating reactors, such as flatbed reactors [30], are usually oriented at a fixed angle toward the sky. They can benefit from diffuse light but present a limited reaction yield due to the low light intensity. On the other hand, by concentrating sunlight on the reactor surface to improve efficiency, concentrating reactors such as solar dish concentrators and solar ovens have been realized [29]. However, this type of reactor requires tracking devices; otherwise, the lens focus is lost as the Earth moves.

A possible alternative lies in LSC devices combined with microflow technologies. The device consists of a polymer LSC waveguide in which reactor microchannels are shaped within. The luminophore embedded in the LSC can effectively harvest sunlight and focus the remitted photons towards the reaction channels, maximizing the number of photons that reach the liquid reaction mixture.

This type of structure combines several advantages: (i) the LSCs can exploit efficiently diffuse irradiation; thus, they do not require a tracking device [31]; (ii) as the re-emitted light does not need to travel up to the edges of the LSC waveguide but instead can be focused on the nearest embedded microchannel, it is possible to use high luminophore concentration, increasing the photon flux that reaches the reactants, while keeping self-absorption losses to a minimum [2,32]; (iii) due to the tunability of the luminophore [2], it is possible to select the most appropriate emission wavelength to perform specific photochemical reactions.

One of the first examples of LSC photo-microreactors (LSC-PM) reported a luminescent red dye, Lumogen Red 305 (LR305), embedded in the polymer matrix of the LSC (Figure 3). [32] This dye had been previously used in LSC devices for PV applications. The dye was paired with a common photocatalyst, Methylene Blue (MB) [33], and injected into the reactor microchannels. Carefully selecting the luminophore-catalyst pair is crucial to maximizing solar energy absorption. In this case, the coupling of LR305 with MB is particularly advantageous due to the excellent spectral overlap between the LR305 emission and MB absorption spectra (Figure 3b). As proof of concept, the singlet oxygen-mediated cycloaddition of 9,10-diphenylanthracene (DPA) was used as a benchmark to show the system's capability. A 4.5-fold acceleration of the reaction with a 200 ppm LR305 doped LSC-PM was obtained compared to the reactor without luminophores (Figure 3c). This setup was also shown to work outdoors with scattered cloud cover. Similar to the lab test, the conversion of the dye-sensitized LSC-PM was significantly higher than in the non-sensitized reactor, even if the scattered clouds influenced the final yield.

An improved design based on modulating the residence time of the reactants within the microchannel depending on the amount of light impacting the reactor was shown to adequately handle light fluctuations caused by passing clouds (Figure 3d) [34,35].

A few follow-up studies probed the efficiency limits of the LSC-PM concept, showing that up to 1 m^2 LSC-PM optimized systems could be built, confirming the potential of LSCs as photochemical reactors [36]. The importance of using the fused deposition modeling (FDM) technique to 3D print molds for LSC manufacturing was also demonstrated. Rapid prototyping by 3D printing allowed for several reactor designs to be tested, in which several parameters, such as the number and spacing of channels and flow and collection sections, can be optimized [37].

However, this type of LSC-PM design presents stability issues due to the use of polydimethylsiloxane (PDMS) as a polymer for the waveguide. While PDMS is compatible with aqueous media and some alcohols, most organic solvents are soluble in PDMS, causing swelling of the polymer, leaching of the dye, and overall degradation of the device [38].

Thus, new LSC-PM devices have been designed in which the LSC is physically separated from the PM reactors. For example, a combination of commercially available poly(methyl methacrylate) (PMMA) LSC plates and solvent-resistant perfluoroalkoxy alkane (PFA) capillaries have been used [39]. In this design, chemically resistant capillaries are embedded into an LSC device. Due to the material's higher refractive index compared to PDMS-based LSC-PM, this new design allowed a substantial photon-flux improvement, with 40% more photons directed to the reaction channels, leading to significant rate accelerations [39]. Further, by using PMMA as a polymer matrix, different organic dyes can be introduced into the waveguide to target specific emission wavelengths by downshifting the incident solar light.

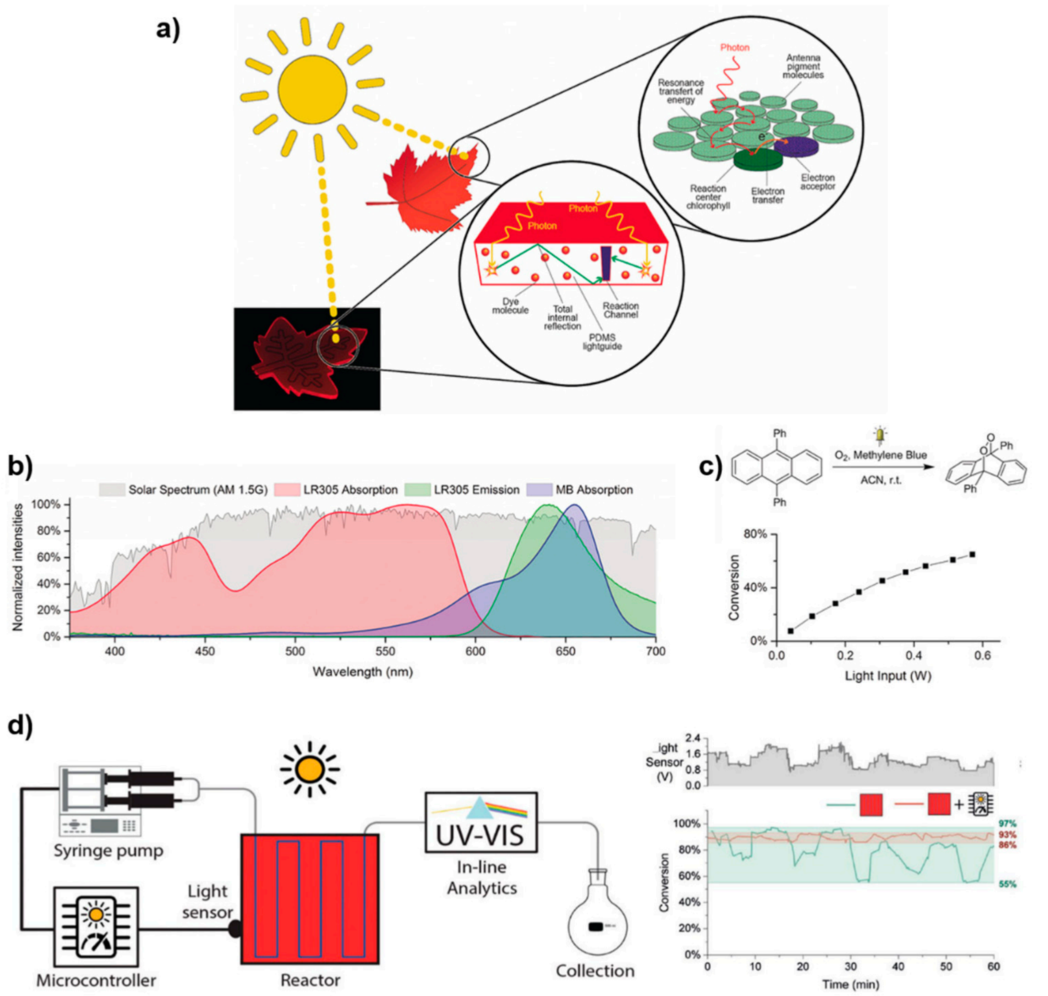

Figure 3. (**a**) Working principle of the luminescent solar concentrator photo-microreactor. (**b**) Absorption and emission spectra of LM305 compared to the absorption of MB. It is possible to observe the excellent spectral overlap between the two dyes. (**c**) The singlet oxygen-mediated cycloaddition of DPA is used as a model reaction. Reprinted with permission from Ref. [32]. Copyright 2017 John Wiley & Sons. (**d**) Improved design of the LSC-PM able to handle light fluctuations caused by passing clouds thanks to a feedback loop. Reprinted with permission from Ref. [34]. Copyright 2018 Royal Society of Chemistry.

All the LSC-PM devices based on polymer matrices present an inherent problem: since the desired emission wavelength is fixed by the luminophore incorporated in the polymer, a dedicated reactor has to be fabricated for different photocatalysts as they require a different emission profile to match their absorption.

To address this issue, Tao et al. modified the LSC-PM design using a liquid dye. In this case, the luminophore is not dispersed within a polymer matrix but instead introduced into a suitable matrix as a fluid [40]. Similar liquid-based luminophores for LSCs have already been shown to be efficient for PV application [21,22].

A schematic illustration of the modified LSC-PM device and light transfer process is shown in Figure 4. The use of a liquid LSC design presents several advantages: (i) luminophores have, in general, better solubility and dispersibility in organic solvents, exhibiting equivalent or higher photoluminescence quantum yield (PLQY) than when embedded in solid matrices [21,41]; (ii) the emission wavelength can be easily changed by replacing the luminophore liquid solution; (iii) the light emission distribution of the fluid in 3D space can be controlled more easily. Overall, this design allows a higher degree of flexibility than the LSC-PM system based on luminophores embedded in polymers.

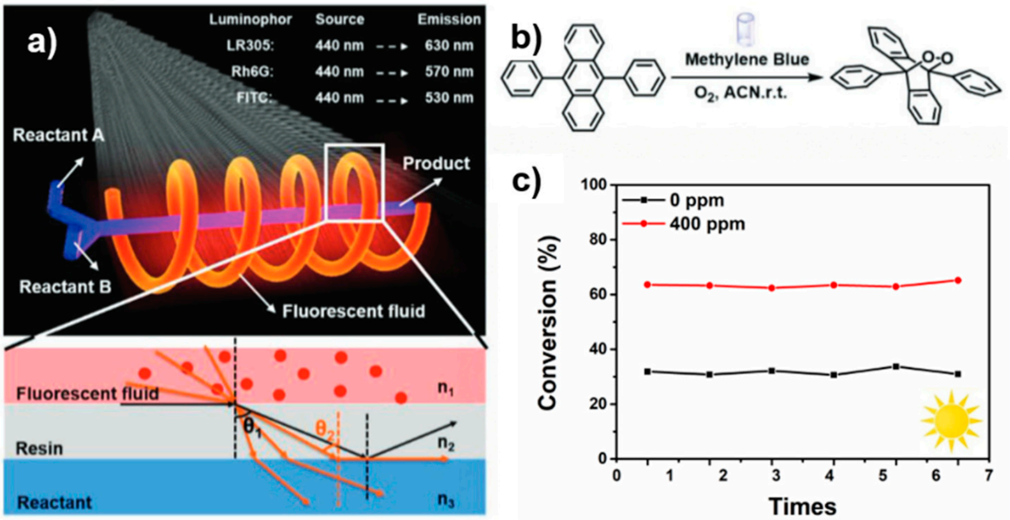

Figure 4. (**a**) Schematic of the modified LSC-PM device based on a coil containing a fluorescent fluid wrapped around the reaction channel. (**b**) The cycloaddition of DPA to the endoperoxide is used as the reaction model to evaluate the performance of the LSC-based reactor. (**c**) Conversion rate for the liquid-based LSC-PM under 1.0 sun (400 ppm of LR305, 15 s residence time); reprinted with permission from Ref. [40]. Copyright 2019 John Wiley & Sons.

Several prototype reactors (~6 cm long) were fabricated by curing a transparent photosensitive 3D-printed resin. The geometry of the reaction channel was optimized as a helix to allow fast mixing compared to the straight channel. In contrast, for the waveguide in which the liquid dye is placed, it was found that a cylindrical shape around the reaction channel presents optimal operation, providing homogeneous irradiation and the highest photon flux. Different dyes have been tested, and the optimized device showed a significant acceleration in conversion rate and apparent reaction kinetics. In particular, under 1 sun illumination, the presence of fluorescent fluids increased the conversion rate by about 30% (Figure 3c).

Subsequent work reported the scale-up of the proposed liquid-based reactor. The authors fabricated reactors with up to eight channels, demonstrating conversions comparable to those achieved in a single-channel reactor [42].

Other LSC designs have been proposed, in which the luminophores are used to increase the intensity of the ultraviolet B region (UV-B, wavelength of 280–315 nm) [43]. Since the UV-B wavelengths in the solar spectrum are less than 5% of the total UV radiation reaching the Earth's surface, these devices have so far only been tested with UV lamps. However, their proof-of-concept could be extended to LSC-PM reactors, in which the UVB emission intensity can be increased by approximately a factor of ten for an 8 W UV lamp [43,44].

In summary, certain requirements are needed to develop an LSC-PM device, such as a durable waveguide material with a high refractive index. Additionally, the luminophore should have a specific emission profile to properly activate the photocatalyst and a narrow spectral distribution to avoid side reactions or degradation of the starting precursors [45]. Distinctive LSC designs are also required to obtain high reaction yields.

As mentioned before, even if the LSC-PM presents several advantages compared to other types of photoreactors, there are still issues and criticalities that need to be further addressed (Table 1). In particular, the system's stability under different light conditions and environments is rarely reported, while this is a critical parameter for their future commercialization.

Table 1. Summary of the critical parameters of LSC-PM devices.

Requirements	Advantages	Issues
• The luminophore should have an emission that overlaps with the absorption of the photocatalyst • The polymer should be stable to the chemicals used for the reaction • Need for specific architecture to direct the majority of the emitted photons toward the reaction channels • Narrow spectral distribution of the luminophore to improve selectivity • Waveguide material should have a smooth surface and high refractive index	• No need for a tracking device • Possibility to use a high concentration of luminophore • It is possible to select the most suitable pair luminophore/photocatalyst to perform different photoreactions • Low-cost materials • They can operate unassisted	• Each reactor can target only a specific photocatalyst as the emission wavelength is fixed • As the final reaction yield is influenced by light fluctuation, there is a need for a feedback loop system • The long-term stability needs to be verified and improved

3. LSC Devices for Applications in Agriculture

3.1. LSC for Controlled Environment Agriculture

According to projections by the Food and Agriculture Organisation (FAO) of the United Nations, by 2050, total food production will have to increase by 70% compared to current volumes to feed the world's growing population [46]. Improved yields and better farm management are therefore a necessity. In this framework, controlled environment agriculture (CEA) could play a fundamental role. CEA is an agricultural method that allows a degree of control over the environmental conditions of plants, such as lighting, temperature, carbon dioxide level, relative humidity, moisture content, and nutrient composition. CEA's goal is to improve crop yield, plants' resilience to climate change, sustainability, and food security [47].

Among the many factors that affect plant growth in a CEA system, light is one of the most important, as it has been shown that not all wavelengths of light give the same response in green plants [48]. Traditionally, light-emitting devices (LED) have been widely used in CEA and crop management due to their ability to control the quality of emitted light [49,50]. However, to operate, they still require external energy input, and they usually present high initial costs for the farmers.

In this framework, LSCs can represent a low-cost and sustainable solution for the modulation of the sunlight impinging on the crops, allowing the emission spectrum to be altered and potentially even redirecting the light.

The first examples of LSC for agricultural uses are based on fluorescence plastic films in which the main objective was to downshift green light towards the red region [51–54]. For example, by using these types of LSC greenhouse covers, tomato yield can be increased by 19.6%, and the number of flowering branches on rose bushes can be increased by 26.7% compared with the sheets without the fluorescent dye [55]. However, these films presented a reduced light transmission in the 400–700 nm range, also known as photosynthetically active radiation (PAR) (Figure 5) [51–54].

For this reason, new combinations of luminescent pigments have been introduced, allowing absorb ultraviolet radiation to be absorbed and downshifting that into PAR, increasing the amount of useful light for the growth of strawberries [57]. For example, it was observed that by using a blue pigment with emissions of up to 480 nm, strawberry production could be increased by 11%. In another approach, by using a photoluminescent phosphor with suitable excitation/emission properties, such as $Ca_{0.4}Sr_{0.6}S:Eu^{2+}$, it was shown that the photosynthetic activity (measured as CO_2 assimilation rate) of *Spinacia oleracea* can be improved by more than 25% compared to a purely reflecting reference film [58].

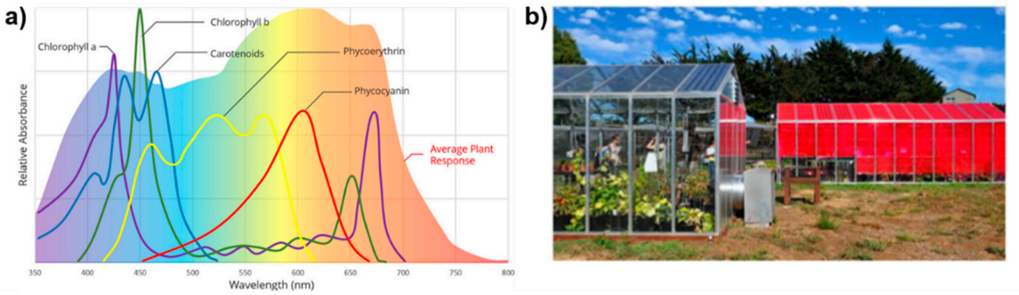

Figure 5. (**a**) The McCree curve, representing the average photosynthetic response of plants at each wavelength, and the absorption curves of different pigments in plants. Reprinted with permission from Ref. [49]. Copyright 2022 American Chemical Society. (**b**) Greenhouse prototypes, one covered with clear glass (left) and one covered with LSC thin film devices (right). Reprinted with permission from Ref. [56]. Copyright 2016 AIP Publishing.

The majority of these LSC films use polyethylene (PE) as waveguide material as it is a low-cost polymer with high transparency and with moderate heat retention, such that it is primarily used in agriculture environments [59]. However, as the film is completely air- and water-proof, there is the requirement to provide forced ventilation and water to the plants shielded by this type of material. To obtain an improved microclimate, nonwoven fabrics of spun-bond polypropylene (PP) have been proposed to replace the PE films. Recently, inorganic luminescent phosphors have also been incorporated into such PP fibers and used as luminescent layers in greenhouses. In this study, the authors compared the dynamics of growth in late cabbage plants (*Olga variety*) and leaf lettuce (Emerald variety) under an ordinary nonwoven PP film and under the spun-bond PP containing Y_2O_2SEu luminophores [60]. Interestingly, the application of the spun-bond containing the phosphorus, despite lowering the overall PAR, led to an increase in the rate of photosynthesis, the water-use efficiency, and the accumulation of the total biomass of plants by 30–50%, showing that luminescent PP-based fabrics could be a promising solution to optimize the plants' growth [60].

In general, the luminophore used in these studies had fixed wavelength emissions, poor photon conversion efficiencies, and in some cases, limited stability. In this context, recently, QDs-based LSCs have been employed successfully in CEA. QDs possess excellent optical properties such as high photon conversion efficiency, a tunable emission spectrum, and improved stability, making them an attractive candidate to replace the dye used in LSCs for CEA [61].

One of the first examples of QD-LSCs for CEA used fiber-LSC with embedded $CuInSe_xS_{2-x}/ZnS$ QDs. This type of QD has been shown to be an excellent luminophore for LSCs for solar windows [62]. Instead of using LSC in thin-film form, in this case, the authors chose to prepare fiber-based LSC, allowing the absorbed sunlight to be delivered to the lower canopy of plants. In particular, the LSC fibers could provide an almost double amount of PAR to the lower canopy leaves converted from absorbed sunlight, which increased the yield of tomatoes in a commercial greenhouse by 7% (Figure 6a–c).

Subsequent work investigated the growth of lettuce in a more controlled experiment in which only the film cover of the greenhouse was varied, while all the other parameters were kept constant (Figure 6d–f) [63]. The authors used three different films: an orange QD film (emission centered at 600 nm), a red QD film (emission centered at 660 nm), and one control with no colour conversion film. The results showed that both colour conversion films gave better results than the control, with increased edible dry mass (13 and 9%), edible fresh mass (11% each), and total leaf area (8 and 13%) for the orange QD and red QD, respectively, compared to the control, despite a reduction of up to 11% in the PAR range observed for the red QD film. These results demonstrated the benefits of using QD films for plant growth with a potential application in space.

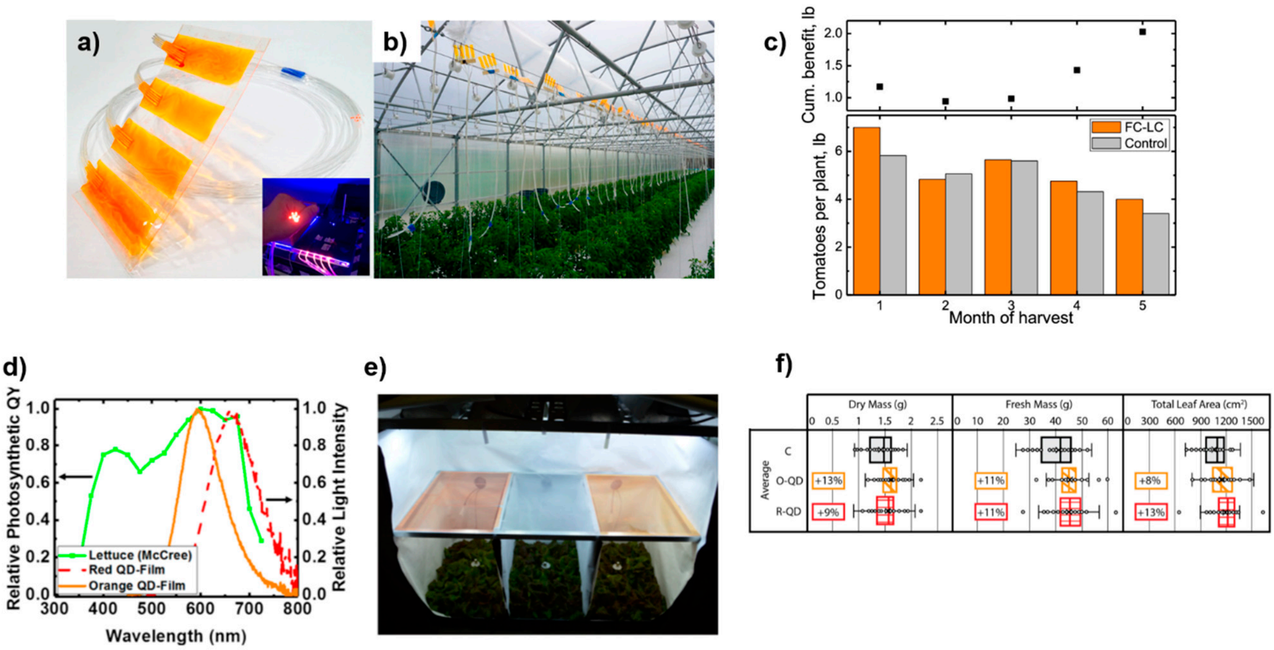

Figure 6. (**a**) Photographs of the fiber-LSC system developed for greenhouses. Inset shows emission from the fibers under blue LED excitation. (**b**) Fiber LSC collectors deployed over a row of tomatoes in a commercial hydroponic greenhouse. (**c**) Comparison of the tomato crop yield with and without using LSC devices; reprinted with permission from Ref [62]. Copyright 2019 American Chemical Society. (**d**) The emission spectra of the two types of QD (orange@600 nm and red@660 nm) overlapped on the photosynthetic response curve for lettuce. (**e**) Photograph of the LSC devices. Three similar areas were used to compare the effects of the different light spectra created by the QD films (left and right) compared to the control film (center) under a similar light intensity. (**f**) Average of three replicate lettuce experiments of measured edible dry mass, edible fresh mass, and total leaf area. Reprinted with permission from ref [63]. Copyright 2021 Springer Nature.

Thus far, various preliminary commercial products, based either on QDs or organic dyes embedded in polymers, have been developed by several companies, such as Ubi-Gro, [64] Lleaf [65], and Solicolture [66].

The main disadvantage of this thin-film technology is that it does not fully exploit the properties of the LSC device. In fact, all these studies use the LSC concept only for its downshifting properties, without exploiting the possibility of concentrating specific wavelengths and obtaining electricity by coupling a PV device.

In this regard, Corrado et al. developed a semi-transparent system combining an LSC with conventional c-Si solar cells named the wavelength selective photovoltaic system (WSPV) by the authors [56]. Instead of positioning the PV devices at the edges of the LSC, the authors placed the cells on the front face, allowing for direct use of sunlight and reducing the traveling distance of the light. The use of the luminescent dye allowed some of the blue and green wavelengths to be absorbed and downshifted into red wavelengths and guided to the solar cell for conversion into electrical energy, while the rest of the sunlight was available to the plants [56]. The placement and types of PV cells used in the LSC panels were varied for performance comparisons, with the best configuration exhibiting a 37% increase in power production compared to the reference. Further, accelerated tests showed that this type of LSC could be stable for up to 20 years.

In a follow-up study, the same authors reported the influence of their WSPV device on tomato photosynthesis [67]. Under low light conditions, the photosynthesis rate of tomatoes was found to be similar, while light-saturated photosynthesis was slightly lower for tomatoes under WSPV. On the other hand, small water-saving potentials were found for plants under WSPV. The results were somewhat inconclusive, and a better understanding of light modulation with this type of device is needed to understand the actual effect on plant growth.

The use of LSCs for CEA systems can also have a negative effect on plant growth. A recent study described the use of an LSC film with a dye luminophore (SG80) in a high-tech greenhouse horticulture facility, and two experimental trials were conducted by growing eggplants [68]. By filtering more than 85% of UV light and 58% of far-red wavelengths, the presence of the film improved energy and resource use efficiency, mainly thanks to an 8% net reduction in heat load and an 18% reduction in water and nutrient consumption of the plants. However, the film strongly reduced the PAR, leading to a 25% reduction in total season fruit yield [68].

While previous thin-film planar solutions could be efficient for improving the growth of plants, they present an intrinsic issue: as the LSC is mounted in a planar configuration, a limited number of internally generated photons can exit the film from the escape light cone into free space. Instead, for optimum plant growth, ideally, a high fraction of the internally generated photons should be extracted in one direction toward photosynthetic organisms.

In recent work, Yin et al. presented an elegant solution based on a spectral-shifting and unidirectional light-extracting photonic LSC that does not require a reflector, and that can be used for improved light use on lettuce cultivation in both greenhouses and indoor farms (Figure 7) [69]. Instead of using a classical planar structure, the LSC based on a LF305 dye was molded with a microdome structure. By employing such a design, the light can be unidirectionally directed toward lettuce cultivation. In particular, more than 70% of the externally extracted light can be redirected in the forward direction and used to increase photosynthesis efficiency. In contrast, the classical planar structure only provides 9% of the internally generated light in the forward direction. The microdome-based LSC film significantly increased the fresh weight and dry weight of lettuce above ground on day 20 after transplanting by 21.7% and 30.3%, respectively. In addition, the presence of the microdome-based LSC led to the extensive growth of lettuce. Overall, a 20% improvement in lettuce production was observed in both indoor facilities with electric lighting and in a greenhouse with natural sunlight [69].

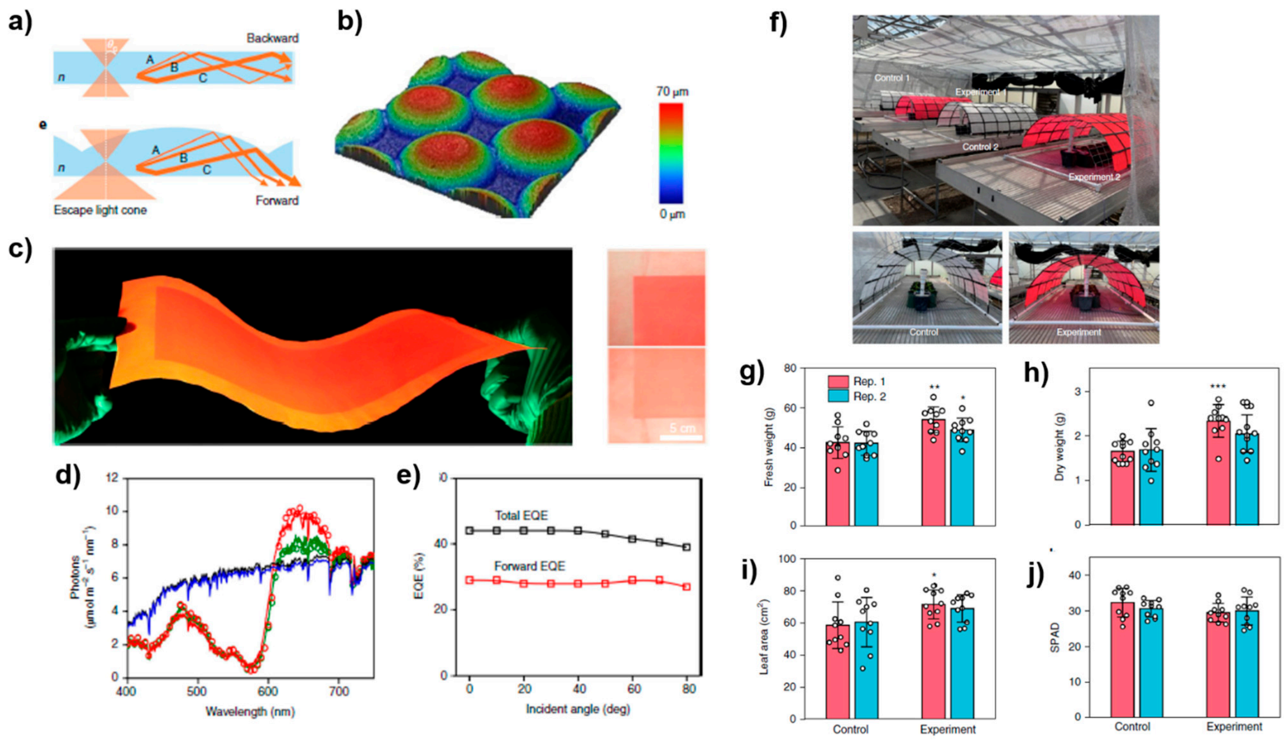

Figure 7. (**a**) Side view of a planar film compared to the unidirectional light-extracting LSC film with surface microdome structures. Thanks to the microstructured surface, rays with incident angles larger

than the critical angle can be extracted in the forward direction. (**b**) Surface morphology of the LSC microdome device. (**c**) Photo of the LSC device with a size of 150 mm × 240 mm under green light illumination. (**d**) The forward spectral irradiance of the LSC device with microdomes (red curve), LSC without surface structuring (green curve), planar fluorophore-free film (black curve), and fluorophore-free film with surface structures (blue curve) under the solar irradiance. (**e**) Total external quantum efficiency (EQE) and forward EQE of the LSC device with microdome surface. (**f**) Photograph of the greenhouse facility. Two domes have LSC devices installed (experiment,) while the two others are the control. Data on the growth of the plants under the LSC device compared to the control: fresh weight (**g**) and dry weight (**h**) of the lettuces, and average leaf area (**i**) and soil-plant analysis development (SPAD) values (**j**) of the lettuces after 20 days from transplantation. (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). Reprinted with permission from Ref [69]. Copyright 2021 Springer Nature.

Overall, to fabricate an LSC device for CEA applications, the system needs to satisfy the following requirements (Table 2): because each plant has a specific need for certain light wavelengths, the appropriate luminophore must be selected; absorption of light by the luminophore should not excessively reduce PAR; moreover, to compensate for this reduction, ideally, the luminophore should have a high quantum yield. Although thin-film devices present a low cost of fabrication and installation, they should be avoided in favor of more complex architectures that direct as much of the re-emitted light as possible toward the plants. In addition, the waveguide material should be chosen judiciously so that it is compatible with the luminophore but also resistant to weathering, UV, etc.

Table 2. Summary of the key parameters of LSC devices for CEA applications.

Requirements	Advantages	Issues
• The luminophore should have a specific emission that is beneficial for the plant growth • The luminophore should have a high quantum yield to compensate for the reduction in the PAR region. • The device should be durable and should have high outdoor resistance (UV, atmospheric agents, temperature, humidity, etc.) • Need for specific architecture to direct the majority of the emitted photons toward the plants	• Semitransparent devices, simple installation • Easy tunability of the luminophore allows to select the most suitable one for the specific crop • Low-cost materials • They do not need any external electrical input to operate • The LSC should be able to increase the crop yields.	• No consensus on the actual effect of the LSC • In thin-film systems, the majority of the emitted radiation is not used by the plants • Different plants require different illumination profile • The long-term stability needs to be verified • In most systems, the LSC is not used for its concentrating properties, but only as a simple downshifting layer.

While LSCs could be a low-cost solution to improve the crop yield, as also visible in Table 3, currently, there is no consensus in the literature on the actual effects of luminescent films and LSCs on fruit yield and quality in major greenhouse crops. This is mainly due to the lack of fundamental and systematic research and calls for more rigorous studies in this field [70].

Table 3. Summary of the type of LSC devices used in CEA and their overall effect on plant growth.

LSC Type	Luminophore	Absorption Range	Emission Range	Overall Effect on PAR	Plant Type	Result	Ref
PVC Thin film	Dye	N/A	660 nm	N/A	maize, melons, tomatoes	Improved growth	[51]
PE-thin film	Dye	UV range	400–480 nm	decreased	N/A	Only 16% of the light was emitted toward the ground	[52]

Table 3. *Cont.*

LSC Type	Luminophore	Absorption Range	Emission Range	Overall Effect on PAR	Plant Type	Result	Ref
PVC-thin film	Dye	400–600 nm	600–700 nm	decreased	N/A	energetic efficiency (21%) of the fluorescence process was not enough to compensate for the loss in the PAR region	[54]
PE-thin film	Dye	400–600 nm	600–700 nm	N/A	tomatoes, roses	19% increase in tomato yield, 26% increase in flowering branches in rose bushes	[55]
LDPE film	Dye	UV range	410–480 nm	increased (+1%)	strawberry	strawberry production to increased +11% (increased fruit number), less sweet	[57]
LDPE film	Dye	UV range	610–630 nm	decreased (−1%)	strawberry	no significant changes	[57]
LDPE film	Dye	up to 600 nm	600–690 nm	decreased (−24%)	strawberry	10% lower fruit production	[57]
Resin coated on reflective film	Phosphor, $Ca_{0.4}Sr_{0.6}S:Eu^{2+}$	up to 600 nm	600–725 nm	N/A	Spinacia oleracea	photosynthetic activity increased by 25%	[58]
PP-fabric	Phosphor, Y2O2SEu	up to 400 nm	600–725 nm	decreased	cabbage, lettuce	total biomass of plants increased by 30–50%, increased rate of photosynthesis and water-use efficiency	[60]
PET embedded acrylate-based Fibers	$CuInSe_xS_{2-x}$/ZnS QDs	up to 500 nm	around 600 nm	increased at lower canopy, decreased otherwise	tomatoes	7% improvement in weight yield	[62]
PET embedded acrylate-based thin films	$CuInSe_xS_{2-x}$/ZnS QDs	up to 600 nm	500–700 nm	no significant change	lettuce	13% increased edible dry mass, 11% increased edible fresh mass, 8% increased leaf area	[63]
PET embedded acrylate-based thin films	$CuInSe_xS_{2-x}$/ZnS QDs	up to 650 nm	600–800 nm	decreased (−11%)	lettuce	9% increased edible dry mass, 11% increased edible fresh mass, 13% increased leaf area	[63]
PMMA thin film + PV embedded	Dye	up to 625 nm	550–700 nm	decreased (5–30%)	tomatoes	no clear difference in fruit yields and quality	[67]
Commercial thin film (Solar Gard)	Dye (SG80)	99% up to 400 nm	Not specified	decreased (−25%)	eggplants	8% decrease in heat load and 18% reduction in water and nutrient consumption, 25% reduction in total fruit yield	[68]
PMMA microdome thin film	Dye (LF305)	up to 600 nm	550–700 nm	decreased	lettuce	20% increase in fresh weight, 30% increase in dry weight, overall extension of the growth of lettuce	[69]

3.2. LSC for Microalgal Production

During the last 60 years, microalgae biomasses have been used to synthesize a wide range of compounds of industrial interest (such as β-carotene, and astaxanthin), food products, pharmacy products, and cosmetics [71]. In addition, microalgae have shown promising results for biofuel production [72] and as a tool for carbon dioxide bioremediation [73].

The rate of microalgae synthesis, and thus the productivity, is strongly correlated with the light absorption properties of microalgae and the quantity and quality (i.e., which wavelengths) of light that reach them. In particular, photoinhibition plays an important role: if the irradiance is too high, it can lead to a decline in the maximum quantum yield of photosynthesis. In many microalgae species, irradiances in the range of 150–400 µmol photons m^{-2} s^{-1} (approximately 10% of full sunlight) can already cause photoinhibition [74,75].

This means that during the majority of the day, the microalgae system operates at low photosynthetic efficiency, absorbing but not effectively using incoming radiation.

Different light distribution systems have been developed to control the light intensity and optimize microalgae growth. Temporal light dilution systems, also known as flashing light systems, are based on inducing dark/light cycles by turbulent mixing of the biomass. This process exposes the microalgae to high light intensity for a short period of time; thus, the average intensity stays below the saturation point. This method can effectively yield a 3-fold increase in algal biomass production [76–78]. While efficient, the temporal light dilution systems require sophisticated mixing systems, which may not be technically feasible for large open pond biomass cultivation and may have high operational costs. In this regard, spatial light dilution methods do not require specific mixing compared to the flashing light systems and thus could be more advantageous. In this method, by using specific light distribution devices, the photon flux density is lowered below the 10% threshold. Systems such as optical fibers [79], parabolic dishes [74], or LSCs can be used to obtain an irradiance below the saturation intensity.

Among all spatial light dilution systems, LSC panels appear to be the most suitable method for microalgal culture systems. In fact, LSC devices are easy to fabricate and do not require a sun tracking system. Further, as it has been shown that exposing photosynthetic organisms to UV light may result in direct photosynthetic damage and causes photoinhibition [80], an LSC allows photons to be downshifted from the UV region to the PAR, reducing the damage to the cells while also yielding an increase in biomass production [81].

In one of the first examples of the LSC concept applied for microalgae production, dyes were incorporated in a double tubular reactor (algae inside and dye solution outside), demonstrating a growth enhancement for certain dyes with high quantum yields and stability, which had suitable absorption/emission spectra for the artificial light sources used [82]. Similarly, dyes embedded in acrylic films have been used as sunlight filters to control the growth of green algae *Chlorella vulgaris* and cyanobacteria *Gloeothece membranacea*. Under different light-modulated spectra, the growth and chlorophylla production were significantly promoted in these two microalgae species [83].

In one of the few examples in which LSC was used coupled to PV devices in conjunction with an algae growth system, Prufert-Bebout et al. demonstrated that microalgae and cyanobacteria grew as well or better under wavelength-selective LSC panels [84]. However, no data were provided on the efficiency of the PV system [84].

Many fluorescent coatings with different dyes and conjugated polymers have been explored and shown the beneficial effect of using this type of LSC device for the growth of microalgae biomasses [81,85–87]. However, the use of common dyes as luminophores for LSCs suffers from the aggregation-caused quenching effect (ACQ), where the fluorescence will be quenched in a high concentration or the aggregate state. This phenomenon limits the usage of high concentrations in film doping, leading to limited spectral shift and poor stability [88,89]. The effect of ACQ can be mitigated by using luminophores that exhibit aggregation-induced emission (AIE) [90]. In molecules such as AIE lumogens (AIEgens), non-radiative deactivation is significantly reduced in the aggregated state due to physical constraints on both intramolecular spins and π-π stacking due to the highly convoluted molecular core [90].

Since their first use in LSC devices [88,91], AIE active molecules have shown promising results, demonstrating a viable design for LSC-PV applications [92,93]. Recently, this concept has also been applied for spectra shifting for augmented photosynthesis of microalgae. For example, AIE active diketopyrrolopyrroles (DPP) have been embedded in PMMA films and used in culturing green algae (*Chlorella* sp.) (Figure 8) [94]. By applying the film to the front cover of a culture flask, it was possible to increase the flux density of photosynthetic photons of orange-red (600–650 nm) by 4% and of deep red (650–700 nm) by 3.4%. This led to an increase in biomass by 26% and in total fatty acid methyl esters by 28.8% [94].

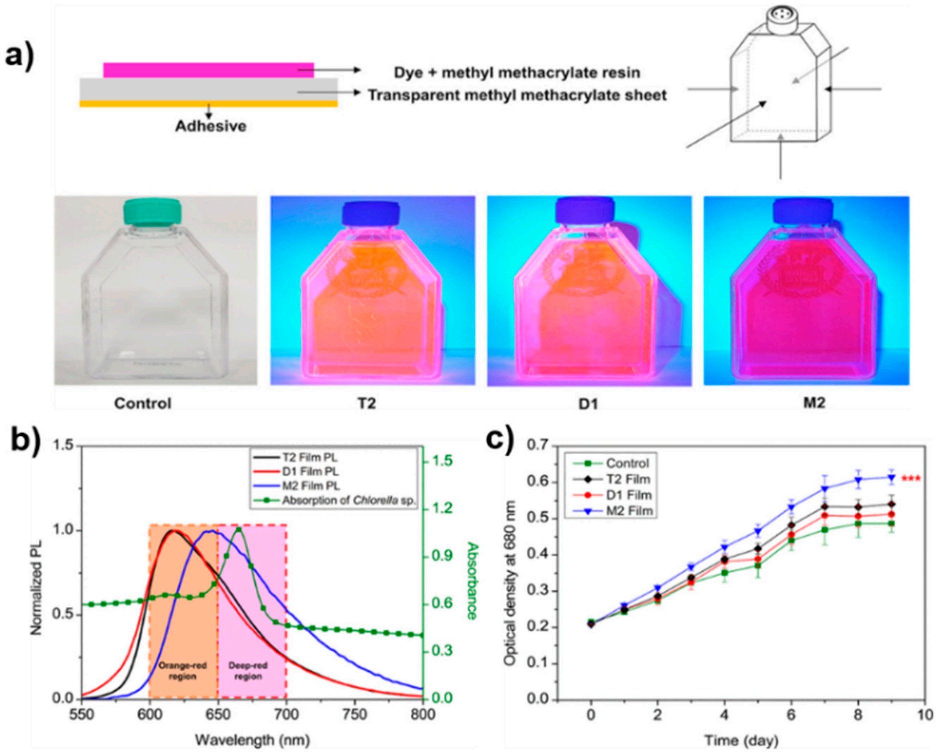

Figure 8. (**a**) Schematic of the culture flask covered with the LSC film and photographs of the device under 365 nm UV lamp irradiation (bottom). (**b**) Normalized emission spectra of the dye-coated LSC films (left axis and solid lines) and the absorbance of *Chlorella* sp. (light axis and dotted line). (**c**) Growth of *Chlorella* sp. monitored at an optical density (OD) of 680 nm. The OD_{680} values of *Chlorella* sp. with different AIEgens dyes (T2, D1, and M2) are 11, 5, and 26% higher, respectively, compared to the control. (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). Reprinted with permission from Ref [94]. Copyright 2021 American Chemical Society.

In follow-up research, by using tailored AIE-DPPs molecules with strong deep-red emissions, an increase in the total fatty acid methyl ester content of microalgae of more than 62% was demonstrated, confirming the promising application of AIEgens to accelerate microalgae mass production [95].

In general, the LSC layers are positioned between the algae culture and light source in a so-called front-side conversion. However, another configuration is possible in which the LSC is placed behind the culture to capture and convert transmitted light. The latter configuration can also be modified with the addition of a reflective backing layer (similar to the mirror configuration used for PV-LSC applications) to have a double-pass effect on the transmitted light back. This configuration is useful only for a dilute concentration of microalgae in which a meaningful amount of light can reach the LSC layer.

Using the backside configuration, Brabec et al. positioned an LSC as a backlight converter integrated into a flat panel algae reactor (Figure 9) [96]. In this case, the luminophore chosen was strontium sulfide doped with divalent europium, $Ca_{0.59}Sr_{0.40}Eu_{0.01}S$. The photoluminescent phosphor was deposited on top of a mirror back-plate and used to culture *H. pluvialis*. The presence of the backside LSC in the reactor increased the algae growth and oxygen production, mainly due to the increased amount of red light in the reactor. In particular, a 36% greater biomass generation at low densities was observed.

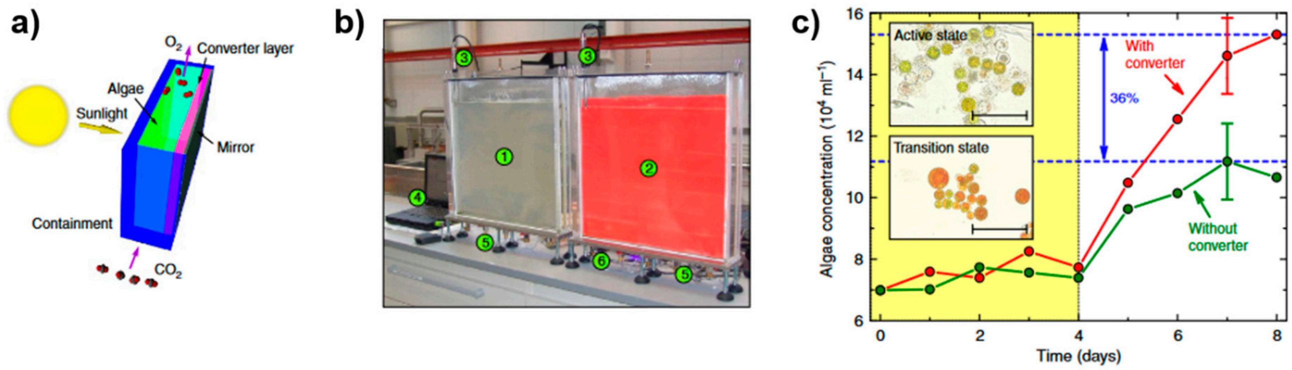

Figure 9. (**a**) Schematic of the backside LSC reactor for the growth of H. pluvialis, where it is partially absorbed. The backside of the reactor is coated with a layer of the red-emitting phosphor $Ca_{0.59}Sr_{0.40}Eu_{0.01}S$. (**b**) Photographs of the LSC device and of the control reactors. (**c**) Algae growth with and without the LSC converter in identical reactors. After an incubation time of about 4 days, significant growth activity can be observed. In particular, the LSC device has a 36% increase in algae concentration in the reactor compared to the control. Reprinted with permission from Ref [96]. Copyright 2013 Springer Nature.

In summary, certain requirements must be met for using an LSC for microalgae growth (Table 4), such as having a luminophore with a high emission quantum yield and absorption in the UV region to reduce cell damage. Additionally, the photon flux density must be carefully controlled to avoid photosaturation and thus inhibition of microalgae growth. The device must also provide uniform light at different depths of the reactor.

Table 4. Summary of the key parameters of LSC devices for microalgal production.

Requirements	Advantages	Issues
• The luminophore should have emission in the PAR region, and possibly filtering UV • The light emitted by the LSC should illuminate the microalgae culture uniformly • The photon flux density should be highly controlled and limited below the 10% threshold (solar irradiance). • The device should be durable and should have high outdoor resistance (UV, atmospheric agents, temperature, humidity, etc.)	• The LSC does not require a tracking device, and works with diffuse illumination • UV-filtering effect reduces damage to the cells • Low-cost materials • The LSC does not need any external electrical input to operate • The LSC increases the growth of the microalgae culture. • LSCs can deliver the sunlight to the depth of the cultures.	• Photolimitation, photosaturation, and photoinhibition are crucial factors that need to be controlled • Issue of shading and light scattering in deep reactors • In a front-light design, part of the reemitted light is lost as it is not directed towards the algae. • The long-term stability needs to be verified

Although the LSC can be an excellent spatial light dilution system for microalgae growth, several issues still need to be addressed, starting from finding the optimal architecture to avoid emission losses and increasing the illumination of deeper areas of the reactor. In addition, there are still no systematic studies on the long-term stability of LSC devices. This parameter is especially critical if the LSC system will be partially submerged in microalgae culture.

4. Conclusions and Outlook

So far, LSC devices have been mostly used as luminophore-doped polymer waveguides coupled with PV cells to separate the area from which the sunlight is collected from where it is converted into electricity. However, LSCs are powerful photonic devices that can be used in a large variety of applications thanks to their high versatility. In particular, in this review, we discussed alternative LSC systems in which sunlight is used as the primary light source, such as solar photosynthetic reactors for organic products, greenhouses for improving plant growth, and solar photobioreactors for microalgae biomass production. In all these cases, the LSC improved the system's efficiency due to its ability to downshift and concentrate specific wavelengths.

In developing such LSC devices, particular attention should be placed on testing the devices under natural light conditions. In fact, even if many luminophores such as organic dyes, phosphors, or QDs report high internal quantum efficiencies, when they are used under low-intense irradiation such as sunlight, they exhibit lower values, and only a smaller amount of incident light is actually converted and exploited by the reaction centers. Further, while increasing the concentration of luminophores could allow greater absorption of sunlight, it can actually be detrimental to the final efficiency due to reabsorption and scattering effects.

Overall, the efficiency of the spectral downshifting with respect to light directed towards the reaction centers (e.g., cell culture, organic photocatalysts, and plants) should be the main parameter to control for obtaining high efficiency.

So far, the majority of LSCs have adopted simple geometries; however, engineering their shape and aspect ratio could yield higher efficiencies. In particular, by borrowing concepts developed for photoreactors based on classical concentrators, it could be possible to integrate them for developing improved LSCs architectures. In this type of system, the LSC device could be placed on the reflector instead of being used as a filter. For example, a parabolic concentrating collector/light distribution system comprised of splitters, optical fibers, and fluorescent reflector has been theoretically proposed for CAE, predicting a 35% improved crop yield [97].

Ultimately, the commercial exploitation of the systems discussed in this review will be a function of how feasible their implementation is, the cost, and the value of the product obtained. One of the main objectives of future research must be to validate the results observed in plant growth and microalgae production to distinguish the impact of spectral light downshifting, light attenuation, and other environmental parameters. Continued work in this field should assess these factors more rigorously and focus on developing/using the highest performing materials, particularly those that can convert non-PAR photons into PAR photons with minimal attenuation of visible light.

Particular attention should be paid to the intensity of light provided to plants. In fact, yield enhancement due to light intensity depends on plant (or algae) type, temperature, and other growth factors. Under a low light regime, the leaves are not saturated with light, and in theory, yield should increase almost linearly. However, once light intensity increases over a certain level, the plant's net photosynthetic rate will eventually saturate, and the yield benefits from higher light levels will be minor and sometimes even harmful. Concerning LSC-based photoreactors for organic products, while few examples have shown to be versatile, most thin-film LSC-PM devices present an intrinsic issue: each reactor can target only a specific photocatalyst as the emission wavelength is fixed. Alternative liquid LSC devices can play a significant role in addressing this problem.

As we have seen for all these LSC-based technologies, a key aspect is controlling the amount and energy of photons delivered to reaction centers, whether photocatalysts or photoreceptors in plants or algae. Therefore, future research should focus on improving LSC systems to achieve the optimal (and not maximum) delivery of photon flux to as many reaction centers as possible, with minimal temporal and spatial fluctuations. Overall, LSCs are a fascinating class of devices, and while their primary use is mainly as solar windows, they can also be employed in other systems, especially those where wavelength selectivity and concentrated light are major requirements. Before LSC devices can be successfully exploited commercially, new fluorophores and waveguide materials should be further investigated. In addition, there is a strong need for real-world prototypes and life-cycle assessments on scaled-up LSC devices.

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References

1. Debije, M.G.; Verbunt, P.P. Thirty years of luminescent solar concentrator research: Solar energy for the built environment. *Adv. Energy Mater.* **2012**, *2*, 12–35. [CrossRef]
2. McKenna, B.; Evans, R.C. Towards efficient spectral converters through materials design for luminescent solar devices. *Adv. Mater.* **2017**, *29*, 1606491. [CrossRef] [PubMed]
3. Shurcliff, W.A. Radiance Amplification by Multi-Stage Fluorescence System. *J. Opt. Soc. Am.* **1951**, *41*, 209. [CrossRef]
4. Weber, W.; Lambe, J. Luminescent greenhouse collector for solar radiation. *Appl. Opt.* **1976**, *15*, 2299–2300. [CrossRef]
5. Levitt, J.A.; Weber, W.H. Materials for luminescent greenhouse solar collectors. *Appl. Opt.* **1977**, *16*, 2684–2689. [CrossRef]
6. Van Sark, W.G.; Barnham, K.W.; Slooff, L.H.; Chatten, A.J.; Büchtemann, A.; Meyer, A.; McCormack, S.J.; Koole, R.; Farrell, D.J.; Bose, R. Luminescent Solar Concentrators-A review of recent results. *Opt. Express* **2008**, *16*, 21773–21792. [CrossRef]
7. Currie, M.J.; Mapel, J.K.; Heidel, T.D.; Goffri, S.; Baldo, M.A. High-efficiency organic solar concentrators for photovoltaics. *Science* **2008**, *321*, 226–228. [CrossRef]
8. Roncali, J. Luminescent solar collectors: Quo vadis? *Adv. Energy Mater.* **2020**, *10*, 2001907. [CrossRef]
9. Yablonovitch, E. Thermodynamics of the fluorescent planar concentrator. *JOSA* **1980**, *70*, 1362–1363. [CrossRef]
10. Bronstein, N.D.; Yao, Y.; Xu, L.; O'Brien, E.; Powers, A.S.; Ferry, V.E.; Alivisatos, A.P.; Nuzzo, R.G. Quantum dot luminescent concentrator cavity exhibiting 30-fold concentration. *ACS Photonics* **2015**, *2*, 1576–1583. [CrossRef]
11. Meinardi, F.; Bruni, F.; Brovelli, S. Luminescent solar concentrators for building-integrated photovoltaics. *Nat. Rev. Mater.* **2017**, *2*, 17072. [CrossRef]
12. Zhao, Y.; Meek, G.A.; Levine, B.G.; Lunt, R.R. Near-infrared harvesting transparent luminescent solar concentrators. *Adv. Opt. Mater.* **2014**, *2*, 606–611. [CrossRef]
13. Debije, M.G.; Verbunt, P.P.; Nadkarni, P.J.; Velate, S.; Bhaumik, K.; Nedumbamana, S.; Rowan, B.C.; Richards, B.S.; Hoeks, T.L. Promising fluorescent dye for solar energy conversion based on a perylene perinone. *Appl. Opt.* **2011**, *50*, 163–169. [CrossRef] [PubMed]
14. Zhang, B.; Zhao, P.; Wilson, L.J.; Subbiah, J.; Yang, H.; Mulvaney, P.; Jones, D.J.; Ghiggino, K.P.; Wong, W.W. High-performance large-area luminescence solar concentrator incorporating a donor–emitter fluorophore system. *ACS Energy Lett.* **2019**, *4*, 1839–1844. [CrossRef]
15. Zhao, Y.; Lunt, R.R. Transparent luminescent solar concentrators for large-area solar windows enabled by massive stokes-shift nanocluster phosphors. *Adv. Energy Mater.* **2013**, *3*, 1143–1148. [CrossRef]
16. Binnemans, K. Lanthanide-based luminescent hybrid materials. *Chem. Rev.* **2009**, *109*, 4283–4374. [CrossRef]
17. Nolasco, M.M.; Vaz, P.M.; Freitas, V.T.; Lima, P.P.; André, P.S.; Ferreira, R.A.; Vaz, P.D.; Ribeiro-Claro, P.; Carlos, L.D. Engineering highly efficient Eu (III)-based tri-ureasil hybrids toward luminescent solar concentrators. *J. Mater. Chem. A* **2013**, *1*, 7339–7350. [CrossRef]
18. Meinardi, F.; Colombo, A.; Velizhanin, K.A.; Simonutti, R.; Lorenzon, M.; Beverina, L.; Viswanatha, R.; Klimov, V.I.; Brovelli, S. Large-area luminescent solar concentrators based on 'Stokes-shift-engineered'nanocrystals in a mass-polymerized PMMA matrix. *Nat. Photonics* **2014**, *8*, 392–399. [CrossRef]
19. Zhao, H.; Zhou, Y.; Benetti, D.; Ma, D.; Rosei, F. Perovskite quantum dots integrated in large-area luminescent solar concentrators. *Nano Energy* **2017**, *37*, 214–223. [CrossRef]
20. Zhao, H.; Benetti, D.; Tong, X.; Zhang, H.; Zhou, Y.; Liu, G.; Ma, D.; Sun, S.; Wang, Z.M.; Wang, Y.; et al. Efficient and stable tandem luminescent solar concentrators based on carbon dots and perovskite quantum dots. *Nano Energy* **2018**, *50*, 756–765. [CrossRef]
21. Liu, X.; Luo, B.; Liu, J.; Jing, D.; Benetti, D.; Rosei, F. Eco-friendly quantum dots for liquid luminescent solar concentrators. *J. Mater. Chem. A* **2020**, *8*, 1787–1798. [CrossRef]
22. Liu, X.; Benetti, D.; Rosei, F. Semi-transparent luminescent solar concentrators based on plasmon-enhanced carbon dots. *J. Mater. Chem. A* **2021**, *9*, 23345–23352. [CrossRef]

23. Wu, K.; Li, H.; Klimov, V.I. Tandem luminescent solar concentrators based on engineered quantum dots. *Nat. Photonics* **2018**, *12*, 105–110. [CrossRef]
24. Zhou, Y.; Benetti, D.; Fan, Z.; Zhao, H.; Ma, D.; Govorov, A.O.; Vomiero, A.; Rosei, F. Near Infrared, Highly Efficient Luminescent Solar Concentrators. *Adv. Energy Mater.* **2016**, *6*, 1501913. [CrossRef]
25. Griffini, G.; Levi, M.; Turri, S. Novel crosslinked host matrices based on fluorinated polymers for long-term durability in thin-film luminescent solar concentrators. *Sol. Energy Mater. Sol. Cells* **2013**, *118*, 36–42. [CrossRef]
26. Kaniyoor, A.; McKenna, B.; Comby, S.; Evans, R.C. Design and response of high-efficiency, planar, doped luminescent solar concentrators using organic–inorganic di-ureasil waveguides. *Adv. Opt. Mater.* **2016**, *4*, 444–456. [CrossRef]
27. Ciamician, G. The photochemistry of the future. *Science* **1912**, *36*, 385–394. [CrossRef]
28. Cambie, D.; Bottecchia, C.; Straathof, N.J.; Hessel, V.; Noel, T. Applications of continuous-flow photochemistry in organic synthesis, material science, and water treatment. *Chem. Rev.* **2016**, *116*, 10276–10341. [CrossRef]
29. Sambiagio, C.; Noël, T. Flow photochemistry: Shine some light on those tubes! *Trends Chem.* **2020**, *2*, 92–106. [CrossRef]
30. Bahnemann, D. Photocatalytic water treatment: Solar energy applications. *Sol. Energy* **2004**, *77*, 445–459. [CrossRef]
31. Debije, M.G.; Rajkumar, V.A. Direct versus indirect illumination of a prototype luminescent solar concentrator. *Solar Energy* **2015**, *122*, 334–340. [CrossRef]
32. Cambié, D.; Zhao, F.; Hessel, V.; Debije, M.G.; Noël, T. A Leaf-Inspired Luminescent Solar Concentrator for Energy-Efficient Continuous-Flow Photochemistry. *Angew. Chem.* **2017**, *129*, 1070–1074. [CrossRef]
33. Romero, N.A.; Nicewicz, D.A. Organic photoredox catalysis. *Chem. Rev.* **2016**, *116*, 10075–10166. [CrossRef] [PubMed]
34. Zhao, F.; Cambié, D.; Hessel, V.; Debije, M.G.; Noël, T. Real-time reaction control for solar production of chemicals under fluctuating irradiance. *Green Chem.* **2018**, *20*, 2459–2464. [CrossRef]
35. de Oliveira, G.X.; Lira, J.O.; Cambié, D.; Noël, T.; Riella, H.G.; Padoin, N.; Soares, C. CFD analysis of a luminescent solar concentrator-based photomicroreactor (LSC-PM) with feedforward control applied to the synthesis of chemicals under fluctuating light intensity. *Chem. Eng. Res. Des.* **2020**, *153*, 626–634. [CrossRef]
36. Cambié, D.; Zhao, F.; Hessel, V.; Debije, M.G.; Noël, T. Every photon counts: Understanding and optimizing photon paths in luminescent solar concentrator-based photomicroreactors (LSC-PMs). *React. Chem. Eng.* **2017**, *2*, 561–566. [CrossRef]
37. Zhao, F.; Cambie, D.; Janse, J.; Wieland, E.W.; Kuijpers, K.P.L.; Hessel, V.; Debije, M.G.; Noel, T. Scale-up of a Luminescent Solar Concentrator-Based Photomicroreactor via Numbering-up. *ACS Sustain. Chem. Eng.* **2018**, *6*, 422–429. [CrossRef]
38. Lee, J.N.; Park, C.; Whitesides, G.M. Solvent compatibility of poly (dimethylsiloxane)-based microfluidic devices. *Anal. Chem.* **2003**, *75*, 6544–6554. [CrossRef]
39. Cambié, D.; Dobbelaar, J.; Riente, P.; Vanderspikken, J.; Shen, C.; Seeberger, P.H.; Gilmore, K.; Debije, M.G.; Noël, T. Energy-efficient solar photochemistry with luminescent solar concentrator based photomicroreactors. *Angew. Chem.* **2019**, *131*, 14512–14516. [CrossRef]
40. Zhang, L.; Zhu, Z.; Liu, B.; Li, C.; Yu, Y.; Tao, S.; Li, T. Fluorescent Fluid in 3D-Printed Microreactors for the Acceleration of Photocatalytic Reactions. *Adv. Sci.* **2019**, *6*, 1900583. [CrossRef]
41. Shcherbatyuk, G.; Inman, R.; Wang, C.; Winston, R.; Ghosh, S. Viability of using near infrared PbS quantum dots as active materials in luminescent solar concentrators. *Appl. Phys. Lett.* **2010**, *96*, 191901. [CrossRef]
42. Zhu, Z.; Yang, L.; Yu, Y.; Zhang, L.; Tao, S. Scale-up design of a fluorescent fluid photochemical microreactor by 3D printing. *ACS Omega* **2020**, *5*, 7666–7674. [CrossRef] [PubMed]
43. Niu, W.; Zheng, Y.; Li, Y.; Du, L.; Liu, W. Photochemical microfluidic synthesis of vitamin D3 by improved light sources with photoluminescent substrates. *Chin. J. Chem. Eng.* **2021**, *29*, 204–211. [CrossRef]
44. Fan, J.; Zheng, Y.; Yang, Y.; Du, L.; Wang, Y. Enhancement of ultraviolet B irradiation with a photoluminescent composite film and its application in photochemical microfluidic synthesis. *Ind. Eng. Chem. Res.* **2020**, *59*, 12870–12878. [CrossRef]
45. Buzzetti, L.; Crisenza, G.E.; Melchiorre, P. Mechanistic studies in photocatalysis. *Angew. Chem. Int. Ed.* **2019**, *58*, 3730–3747. [CrossRef]
46. OECD/FAO. *OECD-FAO Agricultural Outlook 2021–2030*; OECD Publishing Paris: Paris, France, 2021.
47. Benke, K.; Tomkins, B. Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustain. Sci. Pract. Policy* **2017**, *13*, 13–26. [CrossRef]
48. McCree, K.J. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. *Agric. Meteorol.* **1971**, *9*, 191–216. [CrossRef]
49. Kozai, T. Why LED lighting for urban agriculture? In *LED Lighting for Urban Agriculture*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 3–18.
50. Neo, D.C.J.; Ong, M.M.X.; Lee, Y.Y.; Teo, E.J.; Ong, Q.; Tanoto, H.; Xu, J.; Ong, K.S.; Suresh, V. Shaping and Tuning Lighting Conditions in Controlled Environment Agriculture: A Review. *ACS Agric. Sci. Technol.* **2022**, *2*, 3–16. [CrossRef]
51. Zarka, Y.; Zarka, A. New PVC fluorescent film for cladding greenhouses, the results from three years' trials. *Plasticulture* **1990**, *85*, 6–16.
52. Pearson, S.; Wheldon, A.; Hadley, P. Radiation transmission and fluorescence of nine greenhouse cladding materials. *J. Agric. Eng. Res.* **1995**, *62*, 61–69. [CrossRef]
53. Hammam, M.; El-Mansy, M.; El-Bashir, S.; El-Shaarawy, M. Performance evaluation of thin-film solar concentrators for greenhouse applications. *Desalination* **2007**, *209*, 244–250. [CrossRef]

54. Kittas, C.; Baille, A. Determination of the spectral properties of several greenhouse cover materials and evaluation of specific parameters related to plant response. *J. Agric. Eng. Res.* **1998**, *71*, 193–202. [CrossRef]
55. Novoplansky, A.; Sachs, T.; Cohen, D.; Bar, R.; Bodenheimer, J.; Reisfeld, R. Increasing plant productivity by changing the solar spectrum. *Sol. Energy Mater.* **1990**, *21*, 17–23. [CrossRef]
56. Corrado, C.; Leow, S.W.; Osborn, M.; Carbone, I.; Hellier, K.; Short, M.; Alers, G.; Carter, S.A. Power generation study of luminescent solar concentrator greenhouse. *J. Renew. Sustain. Energy* **2016**, *8*, 043502. [CrossRef]
57. Hemming, S.; Van Os, E.; Hemming, J.; Dieleman, J. The effect of new developed fluorescent greenhouse films on the growth of Fragaria × ananassa 'Elsanta'. *Eur. J. Hortic. Sci.* **2006**, *71*, 145–154.
58. Xia, Q.; Batentschuk, M.; Osvet, A.; Richter, P.; Häder, D.P.; Schneider, J.; Brabec, C.J.; Wondraczek, L.; Winnacker, A. Enhanced photosynthetic activity in Spinacia oleracea by spectral modification with a photoluminescent light converting material. *Opt. Express* **2013**, *21*, A909–A916. [CrossRef]
59. Puoci, F.; Iemma, F.; Spizzirri, U.G.; Cirillo, G.; Curcio, M.; Picci, N. Polymer in agriculture: A review. *Am. J. Agric. Biol. Sci.* **2008**, *3*, 299–314. [CrossRef]
60. Khramov, R.N.; Kreslavski, V.D.; Svidchenko, E.A.; Surin, N.M.; Kosobryukhov, A.A. Influence of photoluminophore-modified agro textile spunbond on growth and photosynthesis of cabbage and lettuce plants. *Opt. Express* **2019**, *27*, 31967–31977. [CrossRef]
61. Talapin, D.V.; Lee, J.-S.; Kovalenko, M.V.; Shevchenko, E.V. Prospects of colloidal nanocrystals for electronic and optoelectronic applications. *Chem. Rev.* **2010**, *110*, 389–458. [CrossRef]
62. Makarov, N.S.; Ramasamy, K.; Jackson, A.; Velarde, A.; Castaneda, C.; Archuleta, N.; Hebert, D.; Bergren, M.R.; McDaniel, H. Fiber-coupled luminescent concentrators for medical diagnostics, agriculture, and telecommunications. *ACS Nano* **2019**, *13*, 9112–9121. [CrossRef]
63. Parrish, C.H.; Hebert, D.; Jackson, A.; Ramasamy, K.; McDaniel, H.; Giacomelli, G.A.; Bergren, M.R. Optimizing spectral quality with quantum dots to enhance crop yield in controlled environments. *Commun. Biol.* **2021**, *4*, 124. [CrossRef] [PubMed]
64. Available online: https://ubigro.com (accessed on 24 June 2022).
65. Available online: https://www.lleafgrow.com (accessed on 24 June 2022).
66. Available online: http://www.soliculture.com (accessed on 24 June 2022).
67. Loik, M.E.; Carter, S.A.; Alers, G.; Wade, C.E.; Shugar, D.; Corrado, C.; Jokerst, D.; Kitayama, C. Wavelength-selective solar photovoltaic systems: Powering greenhouses for plant growth at the food-energy-water nexus. *Earth's Future* **2017**, *5*, 1044–1053. [CrossRef]
68. Chavan, S.G.; Maier, C.; Alagoz, Y.; Filipe, J.C.; Warren, C.R.; Lin, H.; Jia, B.; Loik, M.E.; Cazzonelli, C.I.; Chen, Z.H.; et al. Light-limited photosynthesis under energy-saving film decreases eggplant yield. *Food Energy Secur.* **2020**, *9*, e245. [CrossRef]
69. Shen, L.; Lou, R.; Park, Y.; Guo, Y.; Stallknecht, E.J.; Xiao, Y.; Rieder, D.; Yang, R.; Runkle, E.S.; Yin, X. Increasing greenhouse production by spectral-shifting and unidirectional light-extracting photonics. *Nat. Food* **2021**, *2*, 434–441. [CrossRef]
70. He, X.; Maier, C.; Chavan, S.G.; Zhao, C.-C.; Alagoz, Y.; Cazzonelli, C.; Ghannoum, O.; Tissue, D.T.; Chen, Z.-H. Light-altering cover materials and sustainable greenhouse production of vegetables: A review. *Plant Growth Regul.* **2021**, *95*, 1–17. [CrossRef]
71. Olaizola, M. Commercial development of microalgal biotechnology: From the test tube to the marketplace. *Biomol. Eng.* **2003**, *20*, 459–466. [CrossRef]
72. Huang, G.; Chen, F.; Wei, D.; Zhang, X.; Chen, G. Biodiesel production by microalgal biotechnology. *Appl. Energy* **2010**, *87*, 38–46. [CrossRef]
73. Chiu, S.-Y.; Kao, C.-Y.; Huang, T.-T.; Lin, C.-J.; Ong, S.-C.; Chen, C.-D.; Chang, J.-S.; Lin, C.-S. Microalgal biomass production and on-site bioremediation of carbon dioxide, nitrogen oxide and sulfur dioxide from flue gas using *Chlorella* sp. cultures. *Bioresour. Technol.* **2011**, *102*, 9135–9142. [CrossRef]
74. Tredici, M.R.; Zittelli, G.C. Efficiency of sunlight utilization: Tubular versus flat photobioreactors. *Biotechnol. Bioeng.* **1998**, *57*, 187–197. [CrossRef]
75. Carvalho, A.P.; Silva, S.O.; Baptista, J.M.; Malcata, F.X. Light requirements in microalgal photobioreactors: An overview of biophotonic aspects. *Appl. Microbiol. Biotechnol.* **2011**, *89*, 1275–1288. [CrossRef]
76. Abu-Ghosh, S.; Fixler, D.; Dubinsky, Z.; Iluz, D. Flashing light in microalgae biotechnology. *Bioresour. Technol.* **2016**, *203*, 357–363. [CrossRef] [PubMed]
77. Grobbelaar, J.U. Turbulence in mass algal cultures and the role of light/dark fluctuations. *J. Appl. Phycol.* **1994**, *6*, 331–335. [CrossRef]
78. Grobbelaar, J.U.; Nedbal, L.; Tichý, V. Influence of high frequency light/dark fluctuations on photosynthetic characteristics of microalgae photoacclimated to different light intensities and implications for mass algal cultivation. *J. Appl. Phycol.* **1996**, *8*, 335–343. [CrossRef]
79. Xue, S.; Zhang, Q.; Wu, X.; Yan, C.; Cong, W. A novel photobioreactor structure using optical fibers as inner light source to fulfill flashing light effects of microalgae. *Bioresour. Technol.* **2013**, *138*, 141–147. [CrossRef] [PubMed]
80. Helbling, E.W.; Villafane, V.; Ferrario, M.; Holm-Hansen, O. Impact of natural ultraviolet radiation on rates of photosynthesis and on specific marine phytoplankton species. *Mar. Ecol. Prog. Ser.* **1992**, 89–100. [CrossRef]
81. Delavari Amrei, H.; Ranjbar, R.; Rastegar, S.; Nasernejad, B.; Nejadebrahim, A. Using fluorescent material for enhancing microalgae growth rate in photobioreactors. *J. Appl. Phycol.* **2015**, *27*, 67–74. [CrossRef]

82. Prokop, A.; Quinn, M.; Fekri, M.; Murad, M.; Ahmed, S. Spectral shifting by dyes to enhance algae growth. *Biotechnol. Bioeng.* **1984**, *26*, 1313–1322. [CrossRef]
83. Mohsenpour, S.F.; Richards, B.; Willoughby, N. Spectral conversion of light for enhanced microalgae growth rates and photosynthetic pigment production. *Bioresour. Technol.* **2012**, *125*, 75–81. [CrossRef]
84. Detweiler, A.M.; Mioni, C.E.; Hellier, K.L.; Allen, J.J.; Carter, S.A.; Bebout, B.M.; Fleming, E.E.; Corrado, C.; Prufert-Bebout, L.E. Evaluation of wavelength selective photovoltaic panels on microalgae growth and photosynthetic efficiency. *Algal Res.* **2015**, *9*, 170–177. [CrossRef]
85. Delavari Amrei, H.; Nasernejad, B.; Ranjbar, R.; Rastegar, S. Spectral shifting of UV-A wavelengths to blue light for enhancing growth rate of cyanobacteria. *J. Appl. Phycol.* **2014**, *26*, 1493–1500. [CrossRef]
86. Raeisossadati, M.; Moheimani, N.R. Can luminescent solar concentrators increase microalgal growth on anaerobically digested food effluent? *J. Appl. Phycol.* **2020**, *32*, 3703–3710. [CrossRef]
87. Sforza, E.; Barbera, E.; Bertucco, A. Improving the photoconversion efficiency: An integrated photovoltaic-photobioreactor system for microalgal cultivation. *Algal Res.* **2015**, *10*, 202–209. [CrossRef]
88. Banal, J.L.; White, J.M.; Ghiggino, K.P.; Wong, W.W. Concentrating aggregation-induced fluorescence in planar waveguides: A proof-of-principle. *Sci. Rep.* **2014**, *4*, 4635. [CrossRef] [PubMed]
89. Zhou, H.; Li, J.; Chua, M.H.; Yan, H.; Tang, B.Z.; Xu, J. Poly (acrylate) with a tetraphenylethene pendant with aggregation-induced emission (AIE) characteristics: Highly stable AIE-active polymer nanoparticles for effective detection of nitro compounds. *Polym. Chem.* **2014**, *5*, 5628–5637. [CrossRef]
90. Mei, J.; Hong, Y.; Lam, J.W.; Qin, A.; Tang, Y.; Tang, B.Z. Aggregation-induced emission: The whole is more brilliant than the parts. *Adv. Mater.* **2014**, *26*, 5429–5479. [CrossRef]
91. Banal, J.L.; Ghiggino, K.P.; Wong, W.W. Efficient light harvesting of a luminescent solar concentrator using excitation energy transfer from an aggregation-induced emitter. *Phys. Chem. Chem. Phys.* **2014**, *16*, 25358–25363. [CrossRef]
92. Lyu, G.; Kendall, J.; Meazzini, I.; Preis, E.; Bayseç, S.; Scherf, U.; Clement, S.; Evans, R.C. Luminescent solar concentrators based on energy transfer from an aggregation-induced emitter conjugated polymer. *ACS Appl. Polym. Mater.* **2019**, *1*, 3039–3047. [CrossRef]
93. Lyu, G.; Southern, T.J.; Charles, B.L.; Roger, M.; Gerbier, P.; Clément, S.; Evans, R.C. Aggregation-induced emission from silole-based lumophores embedded in organic–inorganic hybrid hosts. *J. Mater. Chem. C* **2021**, *9*, 13914–13925. [CrossRef]
94. Hwang, T.G.; Kim, G.-Y.; Han, J.-I.; Kim, S.; Kim, J.P. Enhancement of Lipid Productivity of *Chlorella* sp. Using Light-Converting Red Fluorescent Films Based on Aggregation-Induced Emission. *ACS Sustain. Chem. Eng.* **2020**, *8*, 15888–15897. [CrossRef]
95. Hwang, T.G.; Kim, G.-Y.; Han, J.-I.; Park, J.M.; Kim, J.P. Highly efficient light-converting films based on diketopyrrolopyrrole with deep-red aggregation-induced emission for enhancing the lipid productivity of *Chlorella* sp. *Sustain. Energy Fuels* **2021**, *5*, 5205–5215. [CrossRef]
96. Wondraczek, L.; Batentschuk, M.; Schmidt, M.A.; Borchardt, R.; Scheiner, S.; Seemann, B.; Schweizer, P.; Brabec, C.J. Solar spectral conversion for improving the photosynthetic activity in algae reactors. *Nat. Commun.* **2013**, *4*, 2047. [CrossRef] [PubMed]
97. Yalçın, R.A.; Ertürk, H. Improving crop production in solar illuminated vertical farms using fluorescence coatings. *Biosyst. Eng.* **2020**, *193*, 25–36. [CrossRef]