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Broad-range spectral management towards next-generation net-zero energy greenhouses

Gan Huang,*[a] Ewan Gage,[b] Boris Breiner,[c] Monica Saavedra,[c] Dmitry Busko,[a] Norbert J. Janowicz,[d] Dominic S. Wright[d] and Bryce S. Richards*[ae]

Greenhouses enable crop production in challenging climates, ensuring food security through controlled environments. Sustainable development requires addressing the food–energy–water nexus while optimising four key factors: light, temperature, CO_2 levels, and water availability. Advancing next-generation greenhouses demands a transdisciplinary approach, yet existing innovations lack a comprehensive framework for integration. This perspective highlights recent technological advances and challenges, positioning broad-range spectral management as a unifying strategy to regulate all the four factors, and aiming at developing highly-efficient and sustainable net-zero energy greenhouses, paving the way to meet future agricultural demands and contribute to global sustainability goals.

Broader context

Greenhouses are essential for ensuring global food security by enabling crop production under diverse and challenging climates. However, their intensive energy demand for lighting, heating, cooling, CO_2 enrichment, and water management poses a major challenge to sustainability. Current solutions typically address these factors in isolation, lacking a unifying framework for energy-efficient operation. Broad-range spectral management offers a transformative approach by simultaneously utilizing the solar spectrum (0.3–2.5 μm) and the atmospheric transmittance window (8–13 μm) to optimize crop growth and energy balance. By tailoring ultraviolet and green light for spectral shifting, harvesting near-infrared for photovoltaic electricity, and managing infrared bands for dynamic heating or cooling through radiative processes, this strategy enables integrated regulation of light, temperature, CO_2, and water in a net-zero energy manner. Beyond reducing greenhouse energy consumption, it opens pathways for sustainable intensification of agriculture, particularly in regions facing climate stress and resource constraints. For the energy and environmental science community, this perspective highlights how coupling optical engineering, photovoltaics, and thermal management can extend beyond traditional power generation to address the food–energy–water nexus, providing an interdisciplinary pathway towards climate-resilient agriculture and global sustainability.

Main

Greenhouses in modern agriculture play a pivotal role in ensuring global food security.[1] By providing controlled environments, they enable year-round crop production, even in regions with extreme or adverse climatic conditions. As part of the food–energy–water nexus,[2] greenhouses utilise advanced technologies to optimise resource use, *e.g.*, significantly reducing water consumption – up to 90% less than open-field farming in some cases.[3] Greenhouses are essential for achieving sustainable agriculture and meeting the dietary needs of a growing global population, projected to exceed 9.7 billion by 2050.[4] Research estimates that ∼1.2 million acres of agricultural land are covered by greenhouses, located in 130 countries across five continents – clear evidence of their widespread global adoption and importance in modern food systems.[5]

Traditional greenhouses are constructed from transparent glass or plastic materials supported by metal or wooden frames. Advanced greenhouses rely on energy-intensive climate-control systems.[5] This substantial energy consumption often represents the largest contributor to their environmental footprint.[6,7] Recent advances have aimed at improving the overall performance, *e.g.* agri-photovoltaics systems enable simultaneous electricity generation and crop cultivation while optimising land-use efficiency.[8–10] Similarly, spectral-conversion *via* luminescent materials can enhance photosynthetic efficiency by converting underutilised wavelengths (ultraviolet and green) into plant-useful photosynthetically active radiation (PAR).[11] Advances in thermal management include the application of radiative cooling

[a] *Institute of Microstructure Technology, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany. E-mail: gan.huang@kit.edu, bryce.richards@kit.edu*
[b] *Centre for Soil, Agrifood and Biosciences, Cranfield University, Bedford, UK*
[c] *Lambda Energy Ltd., Cambridge, UK*
[d] *Yusef Hamied Department of Chemistry, University of Cambridge, Cambridge CB2 1EW, UK*
[e] *Light Technology Institute, Karlsruhe Institute of Technology, 76133 Karlsruhe, Germany*

technologies to passively dissipate heat,[12–14] glass coatings that reversibly transition from transparent to white to reduce solar gain in hot weather,[15] reducing the need for electricity-driven cooling/ventilation systems. Additionally, innovative systems for water harvesting utilise advanced materials and designs to capture atmospheric moisture, addressing water scarcity challenges.[16] These advancements collectively demonstrate the potential for next-generation greenhouses to overcome traditional limitations, enabling sustainable and resource-efficient food production.

Plant growth is influenced by a complex interplay of four key factors: light, water (including moisture in air/soil), temperature (air/soil), and CO_2 concentration. These factors do not operate in isolation, interacting to impact plant productivity.[17] Achieving net-zero energy (NZE) remains a significant challenge due to the substantial consumption required for microclimate regulation. Additionally, the inherent competition between photosynthesis and photovoltaics for the limited available space and sunlight further complicates the integration of sustainable energy solutions. The pathways towards developing next-generation NZE greenhouses require a transdisciplinary effort. Despite the aforementioned progress, a comprehensive methodology that synergistically integrates these diverse elements is lacking. Addressing this gap is essential for advancing greenhouse technology.

This paper highlights the current advances and challenges, proposing perspectives on potential solutions for realising higher-productivity NZE consumption – illustrated in Fig. 1. Sunlight serves as the sole energy input, providing the PAR spectrum (400–700 nm) for photosynthesis, but potentially so much more. By fully utilising the entire solar spectrum (300–2500 nm) through broad-range spectral management, it is possible to generate electricity and heat while maintaining uncompromised photosynthetic production, and to use them to regulate water, temperature, and CO_2 levels within an integrated, net-zero energy framework. Beyond sunlight, another often-overlooked yet infinite resource is the coldness of the universe. Leveraging radiative cooling within the 8–13 μm wavelength range, this resource can act as a natural heat-sink to regulate temperatures and facilitate the condensation and harvesting of atmospheric moisture for irrigation.

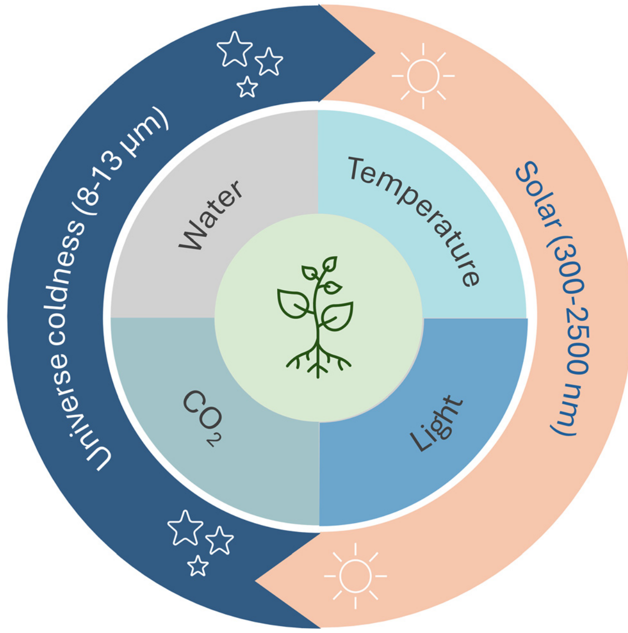

Fig. 1 Schematic representation of the interconnected factors influencing NZE greenhouse performance. The outer ring illustrates the dual influence of solar energy (300–2500 nm) and the universe's coldness (8–13 μm), providing essential energy input and output pathways. The inner segments highlight key environmental variables (light, temperature, CO_2, and water) that interact synergistically to impact plant growth and productivity. The central circle represents the plant system, emphasising its reliance on optimised broad-range spectral management and balanced environmental control for sustainable agriculture.

Key impact factors on plant photosynthesis

Before advancing greenhouse design, it is essential to first understand the key factors that influence plant photosynthesis. Whilst photosynthetic photon flux density thresholds of 100–300 μmol m^{-2} s^{-1} (*i.e.*, 22–65 W m^{-2} in the PAR range) will be sufficient for meaningful CO_2 uptake, saturation of photosynthesis will typically not occur until 800–1200 μmol m^{-2} s^{-1} (*i.e.*, 176–264 W m^{-2} in the PAR range, corresponding to approximately 409–614 W m^{-2} of total solar irradiance, with PAR accounting for around 43% of incident sunlight[18]), depending on species and wider environmental conditions. Spectral composition also affects productivity. Differential absorbance of discrete wavelengths by carotenoids and photosynthetic pigments and excitation imbalance between photosystems result in increased quantum yield for red and blue wavelengths and thus greatest use efficiency.[19] Green wavelengths exhibit reduced quantum yields, thus providing reduced benefits for photosynthesis. While not used directly for photosynthesis, ultraviolet and far-red wavelengths play important roles in modifying physiological and photomorphological processes. Light quality can modify whole-plant productivity through photomorphogenic changes, resulting in changes in light interception (*e.g.* changes to leaf expansion or internode elongation) or through changes in quality parameters such as secondary metabolite accumulation necessary for colour development or nutritive content.[20] The directionality of light, particularly the proportion of diffusivity, also impacts canopy-level photosynthesis rates. Increased light scattering promotes greater uniformity in radiation distribution within the canopy, enhancing penetration to lower canopy layers, promoting increased leaf area index and maximum assimilation rates.[21] Despite well-illustrated benefits of light manipulation (both in spectral composition and intensity), optimum conditions can be difficult to define due to variation between crop types and complex environmental interactions influencing spectral optima.[22]

Low temperatures reduce photosynthesis through reduced enzyme activity rates, particularly of Calvin cycle components, while high temperatures will reduce net assimilation through increased thylakoid membrane leakiness, and photorespiration and lowered rubisco activation.[23] Suboptimal day and night temperatures (and day/night balance) also lower productivity through changes in vegetative development, which impairs light interception (*e.g.* reduced leaf inception and expansion), or promotes changes in flower development and fruit setting such as through reduced pollen viability.[24]

Provision of supplementary CO_2 is required to either avoid CO_2 depletion (<0.4%) or enriching (0.8–1.2%), the latter contributing to elevated net photosynthesis. CO_2 provision represents an additional sustainability challenge, especially if produced *via* fossil fuels combustion. Maintenance of enriched conditions is typically in conflict with other parameters, particularly humidity and temperature control, both realised through ventilation. Humidity must also be tightly controlled – excesses result in reduced transpiration and nutrient availability (especially calcium) and increasing disease risk, while low humidity can reduce photosynthesis through promotion of stomatal closure.[25]

The effects of the aforementioned key parameters on plant growth are summarised in Fig. 2. Optimisation of these parameters is often hindered by the effects of crop type, cultivar and local conditions. Responses are likely to vary with phenological stage, stress susceptibility and acclimatisation capacity, and interactions between factors may have synergistic – or antagonistic – effects. *E.g.*, increased light scattering is liable to reduce leaf temperatures under intense light conditions, offsetting the detrimental effects of high temperatures on net assimilation.[21] Under typical production conditions, light intensity is most often limiting, although the significant interaction between temperature, light levels and CO_2 concentrations (especially enrichment) is unlikely to be beneficial under low-light conditions due to the interplay of alternative limiting factors.

Recent advances in current greenhouses

The primary goal of greenhouse technologies is to create an optimal microclimate by adjusting the aforementioned key factors that influence plant growth. In recent decades, high-tech greenhouses have garnered increasing attention. Emerging technologies such as agri-photovoltaics, light-shifting spectrum management, and advanced thermal and water management have been explored to enhance both crop productivity and energy efficiency.

Typical greenhouses

The first practical greenhouse is credited to Charles Lucien Bonaparte in the early 19th century. Since then, greenhouse technology has evolved, and continues to evolve, at an impressive pace. Today, plastic-film greenhouses (polytunnels see Fig. 3a) are by far the most common for large-scale use worldwide, owing to their cost-effectiveness, scalability, flexibility and ease of installation. The global greenhouse area dedicated to vegetable production is currently estimated at 800 000 hectares.[26]

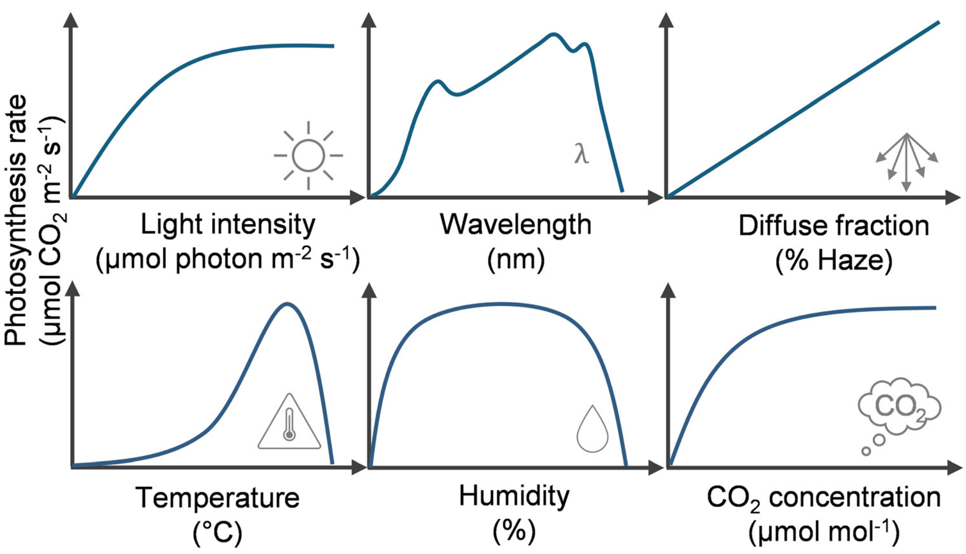

Fig. 2 Key factors affecting plant growth and greenhouse performance. The subplots illustrate the relationships between plant growth and light intensity, spectral composition, diffusivity, temperature, humidity and CO_2 concentration. Comprehensive management is required to consider all these factors holistically, ensuring optimised environmental conditions to maximise plant productivity and sustainability in advanced greenhouse systems. Light intensity and CO_2 concentration typically follow saturation curves, where maximum rates are constrained by factors such as substrate availability or enzymatic capacity. Temperature and humidity exhibit optimal ranges, with deviations reducing photosynthesis through altered biochemical kinetics, stomatal behaviour, photorespiration, and stress responses. Light quality influences photosynthesis through differential pigment absorbance, wavelength-dependent quantum yields, and improved canopy penetration under diffuse light conditions. The inflection point in the wavelength subplot reflects differential absorbance of discrete wavelengths by carotenoids and photosynthetic pigments, with excitation imbalance between photosystems leading to higher quantum yields for red and blue light, while green wavelengths exhibit reduced efficiency for photosynthesis.

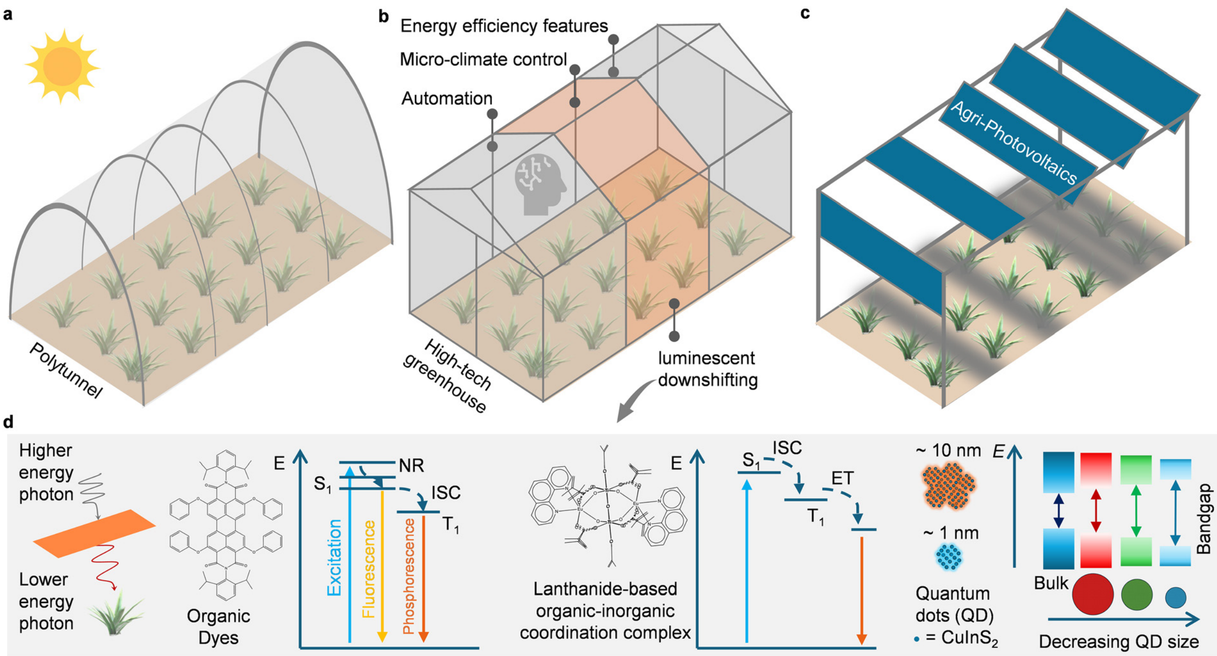

Fig. 3 Recent advances in current greenhouses. (a) The most widely-used plastic-film greenhouses today are polytunnels, owing to cost-effectiveness, scalability, flexibility and ease of installation. (b) High-tech greenhouses usually integrating the functions of climate control, automation, lighting and energy efficiency features. High-tech greenhouses rapidly gaining prominence in commercial agriculture for precision farming and higher yield. (c) Different types of existing agri-photovoltaic systems today based on silicon solar cells. From the left to right, vertically-mounted rigid bifacial photovoltaic-panels, horizontally-mounted rigid photovoltaic panels and panels at a fixed-tilt-angle or with single-axis tracker. The latter two could be either bifacial or monofacial PV modules. All three options incur significant shading of the plants and typically result in reduced crop yield. (d) Examples of luminescent downshifting materials for greenhouse applications including (left) organic dyes (*e.g.*, the perylene Lumogen F Red 305), (middle) lanthanide-based organic–inorganic coordination complexes (*e.g.*, $Eu_2Ti_4O_6(phen)_2(MA)_{10}$), and (right) quantum dots (*e.g.* $CuInS_2$). For each example, a photon energy conversion mechanism resulting in LDS has been depicted.

Modern greenhouses go beyond the original desire to create a warmer microclimate for the cultivation of plants. In their latest evolutionary stage, high-tech greenhouses monitor and control every conceivable variable that affects plant growth, including atmosphere (temperature, humidity, CO_2 concentration), soil conditions (composition, nutrient concentration, humidity, pH), and light (PAR, ultraviolet, infrared, diffusivity)[27] – see Fig. 3b. This is in addition to other factors that influence plant growth that are not specific to greenhouses, *e.g.*, monitoring of plant growth, infection by fungi and fungi-like organisms, and pest control. Furthermore, the need to reduce operating costs wherever possible while maximising crop yield drives the need to make modern greenhouse installations suitable for the implementation of an ever-increasing degree of automation, often combined with the use of artificial intelligence. It is important to point out that crops will typically not stay within a greenhouse through the entirety of their growth cycle. Instead, they are moved, both within the greenhouse as well as from the greenhouse to other locations; modern greenhouses account for this practice by planting crops on movable implements, and making greenhouse interiors accessible to heavy machinery. Advanced climate control and automation comes with substantial energy demands. Depending on location and crop, these can exceed 15 000 GJ ha^{-1} per year.[28] Incorporating renewable energy generation and energy-efficient features is therefore essential for enhancing overall sustainability.

Agri-photovoltaics

Agri-photovoltaics is forecast to have a market share of over 10% of the entire photovoltaics market by 2034,[29] being worth nearly US$14 billion.[30] Typical agri-photovoltaic technologies (illustrated in Fig. 3c) all result in significant shading of the crops. Current practices suggest a maximum ground coverage ratio (area of photovoltaics to land) of $\sim$25% to maintain crop relative yields $>$80%.[31] Although spacing the silicon solar cells to realise 50% transparent photovoltaic modules mounted in a greenhouse roof has realised promising results with plant growth,[32] such technologies still result in significant shading. Indeed, the relative PAR spectrum that lettuces and tomatoes received when operating under solar panels varies massively, from as little as a 7% reduction (compared to the non-agri-voltaic reference case) up to an 88% reduction.[33]

Next-generation agri-photovoltaic technologies circumvent this problem by using spectral splitting techniques to: (i) prioritise crop-growth by delivering the PAR spectrum to the plants; and (ii) utilising the non-PAR photons for electricity generation *via* photovoltaics. These "waste" photons are typically in the ultraviolet, green, and the near-infrared. To achieve this, two different approaches are being pursued. Firstly, thin-film PV technologies have been designed to be semi-transparent in the PAR range. For thin-film PV technologies based on semiconductors, such as amorphous silicon, this typically result in a blue-poor (red-rich) spectrum reaching the crops.[34] Thin-film metal halide perovskite mini-modules with an average visible transparency of over 30% have been developed, with a relatively neutral colour (slightly blue poor).[35] Perhaps the greatest potential lies in organic photovoltaic modules since the absorption bands of the donors and acceptors can be engineered to allow for maximum transparency in the PAR range. However, to date, such organic photovoltaic modules exhibited only about 20% average transmissivity in the PAR range.[36,37] Thus, current OPV technology cannot offer benefit to the PAR spectrum compared to spaced-out opaque silicon solar cells.[38] Secondly, luminescent down-shifting (LDS) layers, can spectrally modify the incident solar spectrum to match the required spectrum better[11,39] plus also enabling waste photons to be harvested by PV – described in more detail below.

Light-shifting spectrum management

Photoluminescent materials for solar irradiance conversion and modification have long been consideration as a means for managing light in plant growth.[40,41] For greenhouses, LDS has been demonstrated to result in significant enhancements to plant growth, crop yield and quality by shifting the ultraviolet light (less beneficial for photosynthesis) into the PAR spectrum. Advancements in this field involve the use of organic dyes, such as Lumogen F series by BASF in the mid-1980s for solar energy conversion and, more recently, quantum dots specifically designed for agricultural applications (*i.e.*, shifting ultraviolet and green components to PAR), which are embedded in plastic films as the emissive materials (Fig. 3d).[42–44] While organic dyes are cost-effective, widely available, and exhibit both strong absorption and high photoluminescent quantum yields, they are prone to photobleaching (photochemical degradation), which limits their operational lifetimes. Conversely, quantum dots, offer potentially longer lifetimes but are costly, challenging to synthesise at scale, can contain toxic elements and may necessitate surface modifications to prevent luminescence quenching within a plastic matrix. Despite these challenges, commercial applications of these technologies have reported notable increases in crop yields, with some claims of improvements of up to 20%.[45,46] Recently lanthanide-based coordination complexes have gained significant interest in greenhouse applications, with varying degrees of success being demonstrated in plant trials (Fig. 3d).[47,48]

Thermal and water management

Temperature plays a critical role in the growth of plants within greenhouses. While greenhouses can efficiently retain heat and maintain warmth in colder climates, dissipating heat in hotter regions poses a significant challenge. Ventilation is the traditional method for releasing excess heat to the ambient environment; however, it is energy-intensive and depends on electricity. Recently, passive daytime radiative cooling (PDRC) technology has garnered considerable attention as a sustainable solution to address this issue.[49] PDRC roof material has high thermal emissivity, allowing effective heat dissipation to the cold universe, while also reflecting ultraviolet and near-infrared radiation to minimise unnecessary heating.[12,13] This dual action helps naturally cool down the greenhouse environment. A more promising approach involves using highly-reflective and thermally-emissive ground covers, which reflect almost all sunlight that reaches the soil and emits heat efficiently. This reduces root zone temperatures by as much as 12.5 °C and significantly improves summer crop yields, with increases of up to 127%.[14] In addition to temperature management, water scarcity remains a pressing global challenge, particularly for greenhouses. Water loss in greenhouses occurs primarily through plant transpiration, soil evaporation, and ventilation, where vapour escapes into the ambient air. A recent innovation utilises advanced hydrogel materials capable of absorbing moisture from the air at high relative humidity during the night.[16] These hydrogels release the captured water during the day under natural sunlight, providing a sustainable source of irrigation water, addressing water scarcity concerns, and reducing greenhouse reliance on external water sources.

Pathway to next-generation greenhouses: comprehensive broad-range spectral management

Despite the above advancements, a unified methodology that effectively integrates these diverse elements remains lacking. Here, we propose a comprehensive broad-range spectral management approach that uses targeted control of different solar wavelength ranges to regulate light, temperature, CO_2 levels, and water availability, offering integrated solutions to enhance greenhouse productivity while achieving net-zero energy operation. Plants in traditional greenhouse designs utilise a small fraction of the solar spectrum for photosynthetic energy capture between 400–700 nm, with the greatest utilisation seen of red (600–700 nm) and blue wavelengths (400–500 nm) although these account for merely 28% of the total incident solar energy under the AM1.5G (Air Mass 1.5 Global) solar spectrum standard.[50] Other wavelengths can influence wider physiological and developmental processes (*e.g.*, UV induction of oxidative stress response, day length perception and sun/shade adaptation utilising far-red (700–750 nm) light) although effects vary with genotypic, phenological and environmental influences. However, the full solar spectrum spans from 300 to 2500 nm, offering untapped potential for energy optimisation. By employing spectral splitting to tailor the use of each segment of sunlight, solar energy utilisation can be significantly improved. Furthermore, the often-overlooked mid-infrared range, where thermal radiation exchanges with the cold universe (8–13 μm), presents additional opportunities for greenhouse cooling and water harvesting from air. A comprehensive broad-range spectral management methodology has high potential for addressing these challenges (see Fig. 4). This section elaborates on this methodology by discussing each wavelength range and its specific role in greenhouse optimisation.

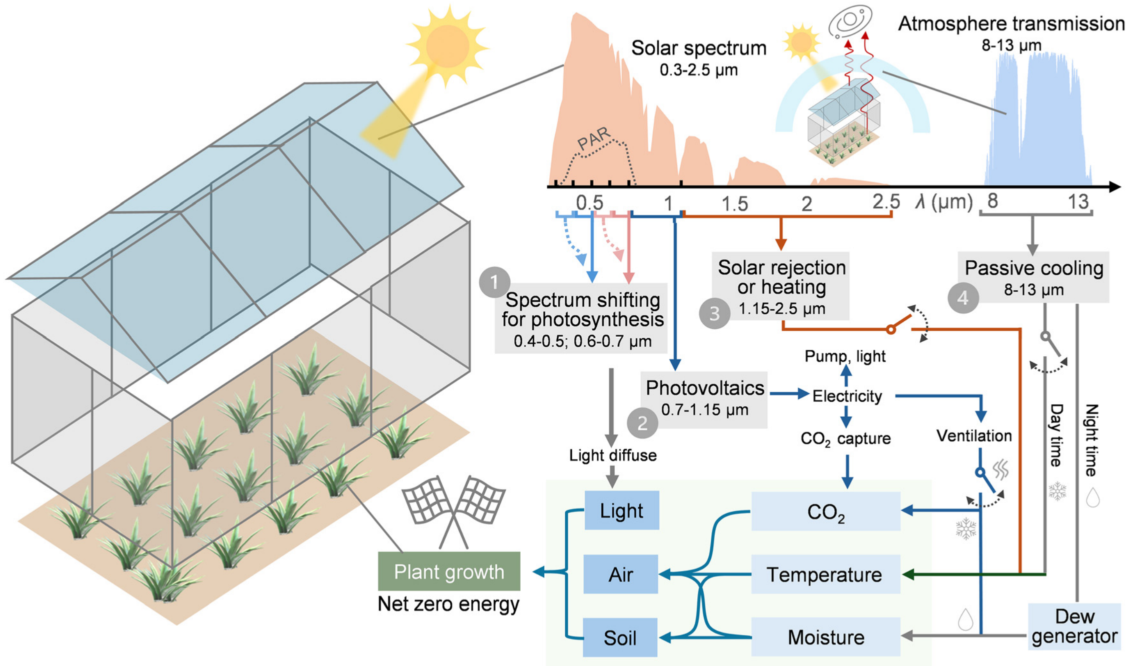

Fig. 4 Conceptual diagram of the comprehensive broad-range spectrum management strategy can lead to the next-generation NZE greenhouse. The spectrum management strategy includes: (1) ultraviolet (300–400 nm) and green (500–600 nm) spectrum shifting for light management; (2) near-infrared spectrum (700–1150 nm) photovoltaic electricity generation for CO_2, temperature and water regulation; (3) short-wavelength infrared spectrum (1150–2500 nm) for tuneable thermal regulation; (4) mid-infrared spectrum radiative cooling (8–13 μm) for temperature and water regulation.

Ultraviolet (300–400 nm) and green (500–600 nm): spectrum shifting for light management

The ultraviolet and green regions of the solar spectrum, which together constitute 20% of total solar energy, are less efficiently utilized for photosynthesis compared to red and blue light. LDS can shift the photons from these spectral regions to wavelength where the PAR peaks (400–500 nm and 600–700 nm), thereby enhancing light availability for plant growth. Micro-textured LDS layers that emit 38–73% of the luminescence in the forward direction (towards the greenhouse floor) have been reported. The performance was worse (38–49%) for thicker (1–5 mm) LDS slabs that had inverted micro-cones on the rear side,[51,52] compared to a thinner foil (210 μm) with micro-dome arrays on the top side (65–73%).[11,53] The latter work also concluded that the growth of 'Buttercrunch' lettuce was effectively enhanced using the LDS foil. Thus, by converting under-utilized spectral energy into a more effective range for plant growth, this strategy enhances greenhouse light-use efficiency and reduces the reliance on artificial LED lighting.

Near-infrared (700–1150 nm): photovoltaic electricity for greenhouse regulation

The near-infrared spectrum (700–1150 nm), which together constitute 34% of total terrestrial sunlight, can be efficiently captured using silicon solar cells to generate electricity, without interfering with photosynthesis. This generated electricity can be used to regulate air temperature, humidity, and CO_2 concentration through active ventilation systems. Additionally, electricity can power CO_2 capture devices[54] that concentrate atmospheric CO_2 inside the greenhouse, directly improving photosynthesis. Other uses include driving heaters, water pumps, sensors, and control systems.

Common silicon PV panels typically achieve an electrical efficiency of approximately 20–23% when utilising the entire solar spectrum (the best silicon PV panel has an efficiency of 25% in the standard condition[55]). This efficiency decreases to around 10% when only the 700–1150 nm spectrum is directed to the silicon PV panel.[56] Considering an annual global horizontal solar irradiance of 1000–2900 kWh m^{-2} per year[57] and restricting the input spectrum to the 700–1150 nm spectrum range, a greenhouse-integrated silicon PV system with integrated spectrum management has the potential to generate 100–290 kWh m^{-2} per year of electricity. In the northern hemisphere, opaque bifacial PV panels could be installed on the north-facing vertical wall of the greenhouse (and *vice versa* in the southern hemisphere), generating approximately 150 kWh per year in northern Europe to 340 kWh per year in the south-western USA, per m^2 of the vertical wall.[58] To estimate electricity generation per unit of greenhouse horizontal area, these values should be multiplied by the ratio of the north wall area to the horizontal area. This approach thus is particularly advantageous when the north wall area is comparable to the greenhouse's horizontal area. While installing PV panels on the north wall is not a spectral management approach (the focus of this perspective), it represents an effective space management strategy, and is included here as a reference.

Through optical engineering, the solar spectrum can be spectrally split to direct each band to its intended function.

For example, a customised dielectric optical filter can separate the spectrum at ∼700 nm into two parts: 300–700 nm directed to the LDS layer for spectrum shifting, and >700 nm directed to silicon PV for electricity generation. This arrangement allows both systems to operate on the same physical area without spectral interference.

Short-wavelength infrared (1150–2500 nm): tuneable thermal regulation

The short-wavelength infrared range (1150–2500 nm), comprising 18% of total solar energy, is challenging to utilise for photovoltaics or LDS. However, it can be harnessed for thermal management. In cold climates, this spectrum can be absorbed and converted into heat to warm the greenhouse. Conversely, in hot climates, this range can be reflected to minimise overheating. This flexibility in energy use or rejection significantly reduces the need for external heating or cooling inputs, enhancing energy efficiency in greenhouses. Considering an annual global horizontal solar irradiance of 1000–2900 kWh m^{-2}, approximately 47–137 kWh m^{-2} solar per year can be harnessed for heating the greenhouses in winters or rejected to reduce cooling energy demands in summers. In summer, a spectrally selective film can be deployed to reflect or block the near-infrared spectrum.[59] In winter, the same retractable or switchable layer can be removed or rolled back to allow NIR transmission for passive heating.

Mid-infrared (8–13 μm): radiative cooling for temperature and water regulation

The mid-infrared spectrum (8–13 μm) allows thermal radiation exchange with the cold universe, providing an untapped source of "cold energy".[60] By using advanced PDRC materials as greenhouse coverings or ground films, heat can be emitted directly into space, thereby lowering the internal temperature. Common soda-lime glass used in greenhouses exhibits high thermal emission, providing approximately 80 W m^{-2} of radiative cooling power.[61] In contrast, well-designed radiative cooling materials can achieve around 100 W m^{-2} cooling power,[61] offering an additional around 43 kWh m^{-2} of cooling compared to glass (assumes cooling is required for three summer months per year). In winter, when greenhouse cooling is unnecessary, radiative cooling can be reduced by deploying a low-emissivity covering. In practice, this can be achieved using a retractable or roll-out film. This film should maintain high transparency to sunlight while exhibiting low emissivity in the mid-infrared range,[62] thereby minimising its impact on other parts of the spectrum.

Additionally, radiative cooling can aid in water harvesting by condensing ambient moisture into liquid water.[63] This can even work during night-time. Recent studies demonstrate that such systems can collect ∼0.1 L m^{-2} per night in arid climates like Dubai[64] and up to ∼1 L m^{-2} per day in temperate regions like Switzerland.[65] With greenhouses typically requiring ∼5 L m^{-2} per day of water for common crops, this approach could substantially alleviate water scarcity issues. In winter, although cooling should be avoided, the mid-infrared window may still be indirectly utilised for water harvesting through condensation of ambient moisture. The main challenge lies in developing multifunctional materials that can simultaneously minimise radiative heat loss of the greenhouse while enabling such water harvesting processes. Future research into dynamic or switchable mid-infrared coatings could provide a pathway toward year-round spectral management tailored to seasonal needs.

Adaptability of the broad-range spectral management framework

The proposed broad-range spectral management framework is designed to be inherently adaptable rather than prescribing a single, fixed spectral configuration. The framework can be tailored by adjusting the spectral splitting, filtering, or light shifting components to deliver crop-specific light intensities and spectral compositions. For instance, solanaceous crops may show the greater benefits from red-enriched spectral shifted light, compared with cucumber which has a higher blue requirement.[66,67] Leafy greens like lettuce thrive under lower intensities and can benefit from diffusive films that improve light uniformity within the canopy. This adaptability can be achieved using modular optical elements, such as removable or switchable films, that can be reconfigured for different crops or seasonal conditions. Furthermore, the framework can incorporate smart control systems linked to environmental sensors, enabling real-time adjustments to spectral transmission based on light intensity, crop type, and growth stage. For example, adjustable roof blades coated with spectral management materials could be rotated to modulate the amount and composition of transmitted light.

NZE analysis

The energy demands of conventional greenhouses vary significantly depending on the climate of their locations. In hot and mixed-humid climate regions that are suitable for effective greenhouse operations and plant cultivation, the annual total energy demand for conventional greenhouses ranges from 150–250 kWh m^{-2} per year.[6] This demand can be significantly reduced by over 50 kWh m^{-2} per year through strategic absorption or rejection of energy in specific wavelength ranges as mentioned above. With PV panels capable of generating 100–290 kWh m^{-2} per year of electricity, the energy requirements of greenhouses in these regions can possibly be met, achieving NZE status. Central to this approach is full-spectrum management, where the entire solar range (300–2500 nm) together with the atmospheric transmittance window (8–13 μm) is managed to balance photosynthetic light use, electricity generation, heating, cooling, and water harvesting within one unified framework. In colder regions, greenhouse energy demands can exceed two times those in milder climates, primarily due to the higher heating requirements during winter. Addressing this challenge may require additional strategies, such as advanced thermal insulation, optimised energy management systems, and hybrid renewable energy integrations. Overall, our analysis shows that the comprehensive broad-range spectral management strategy represents a transformative approach to greenhouse design.

From an economic perspective, the feasibility of next-generation net-zero energy greenhouses employing broad-range spectral management will depend on balancing initial investment costs with long-term operational and productivity gains. Major cost drivers include the fabrication and integration of optical spectral management materials, photovoltaic modules, and smart control infrastructure. These upfront costs can be offset by reductions in heating, cooling, lighting, and CO_2 enrichment energy demand, as well as by improvements in crop yield and quality that may command market premiums. Continued reductions in the price of PV technologies, advanced coatings, and optical components are expected to improve cost-effectiveness over time. While detailed payback time modelling is beyond the scope of this perspective, future research should develop techno-economic frameworks tailored to specific climatic conditions, crop profiles, and operational strategies to quantitatively assess return on investment and accelerate commercial adoption.

Author contributions

G. H. and B. S. R. initiated the concept and coordinated the research efforts. E. G. analysed the key impact factors influencing plant photosynthesis. B. B. and M. S. conducted analyses of typical greenhouse structures and systems. B. S. R. focused on the evaluation of agri-PV systems. N. J. J. and D. S. W. analysed light-shifting technologies. G. H. conducted analyses on thermal and water management and performed the energy balance analysis. All authors contributed collaboratively to proposing pathways for the development of next-generation greenhouses.

Conflicts of interest

The authors declare no competing interests.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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