ACS
AGRICULTURAL
SCIENCE & TECHNOLOGY

pubs.acs.org/acsagscitech
Review

A Tale of Two Approaches: Photosynthetic Augmentation via Nanobionics and Solid-State Fluorescence

Konstantinos T. Kotoulas, Andrew D. Burrows, Gareth Cave, and Ming Xie*

Cite This: https://doi.org/10.1021/acsagscitech.5c00975
Read Online
ACCESS | Metrics & More | Article Recommendations

ABSTRACT: Global food demand is projected to rise by nearly 50% by 2050, placing unprecedented pressure on agricultural productivity. Photosynthesis, the biological foundation of crop growth, is intrinsically constrained by its limited utilization of the solar spectrum, as only 43% of incoming solar energy falls within the photosynthetically active radiation (PAR) range. This review evaluates two strategies that can be used to overcome these spectral limitations: external light modulation via solid-state fluorescence and internal augmentation through plant nanobionics. Solid-state fluorescence employs luminescent films and greenhouse coatings that convert harmful or underutilized ultraviolet radiation into PAR, enhancing canopy-level light quality. Nanobionics integrates engineered nanomaterials into plant tissues, where they function as artificial antennae that expand absorption spectra and may transfer energy directly to chlorophyll via Förster Resonance Energy Transfer (FRET) or direct electron transfer. However, challenges remain in validating FRET in vivo (requiring fluorescence lifetime imaging microscopy), understanding nanomaterial environmental fate, and scaling these technologies economically. This review synthesizes current findings, highlights mechanistic uncertainties, and outlines future pathways toward integrating photonic technologies into sustainable agriculture.

KEYWORDS: *plant nanobionics, luminescent agricultural composites, sustainable agriculture, spectral conversion, photosynthetic augmentation*

1. INTRODUCTION

1.1. Overcoming the Spectral Limits of Photosynthesis

The dual challenges of feeding a population projected to reach nearly 10 billion by 2050 and mitigating climate change, impacts demand for transformative agricultural innovation.[1] Conventional intensification is limited by land scarcity, fertilizer dependence, and ecological damage. Enhancing photosynthetic efficiency represents a sustainable route to higher yields. Despite its central role, photosynthesis is inefficient: C_3 crops such as wheat or rice achieve a theoretical maximum solar energy to crop biomass conversion of only 4.6%, while C_4 crops such as maize achieve 6.0%.[2] This inefficiency arises because chlorophylls absorb mainly red and blue wavelengths, leaving much of the solar spectrum (green, UV, far-red) unused.[3] A detrimental factor in hindrances to photosynthetic systems remains to be inefficiency in the light harvesting and light absorption processes within key plant pigments. This is a consequence of primarily only blue and red light being useful in photosynthesis, with other wavelengths of the light spectrum such as green, UV and far-red being underutilized.[4]

1.2. Case for Photosynthetic Augmentation

Since only a fraction of incident light from the sun drives carbon fixation, improving spectral use efficiency could result in major photosynthetic improvements. By redirecting, converting, or supplementing light that would otherwise be wasted, photosynthesis can be pushed beyond its natural spectral constraints. The first method covered in this review is external light modulation (Indirect Augmentation), which include luminescent films and coatings that down-convert UV radiation into PAR, enriching the plant's spectral environment (Figure 1). The second method involves Internal Nanobionics (Direct Augmentation), in which engineered nanomaterials are integrated into leaves and chloroplasts, acting as artificial antennae to extend absorption and enable efficient energy transfer to photosystems (Figure 1). These strategies represent a shift from purely genetic or biochemical crop improvement toward materials-enabled photonic agriculture.

2. SOLAR SPECTRUM AND PLANT PHOTOBIOLOGY

Light quality governs plant productivity, morphology, and stress tolerance. A nuanced understanding of how different spectral bands interact with plant physiology underpins augmentation strategies.

2.1. Photosynthetically Active Radiation (PAR)

PAR is formally defined as the spectral range of solar radiation between 400 and 700 nm that photosynthetic organisms can harness for photosynthesis (Figure 2). Within the PAR band, however, different colors of light are not functionally

Received: October 29, 2025
Revised: December 22, 2025
Accepted: December 24, 2025

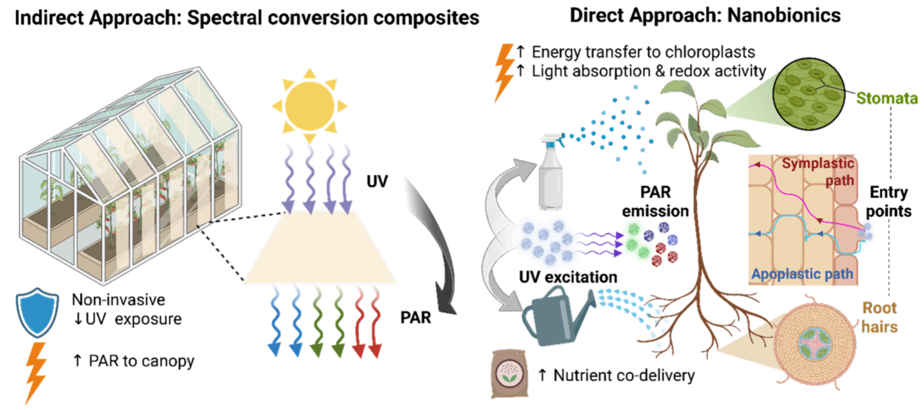

Figure 1. Comparative schematic of indirect (external) and direct (internal) strategies for photosynthetic augmentation. The indirect approach (left) employs spectral conversion materials, such as luminescent films and coatings for greenhouses. The direct approach (right) uses plant nanobionics, where engineered nanomaterials are introduced into plant tissues via foliar spray or root uptake.

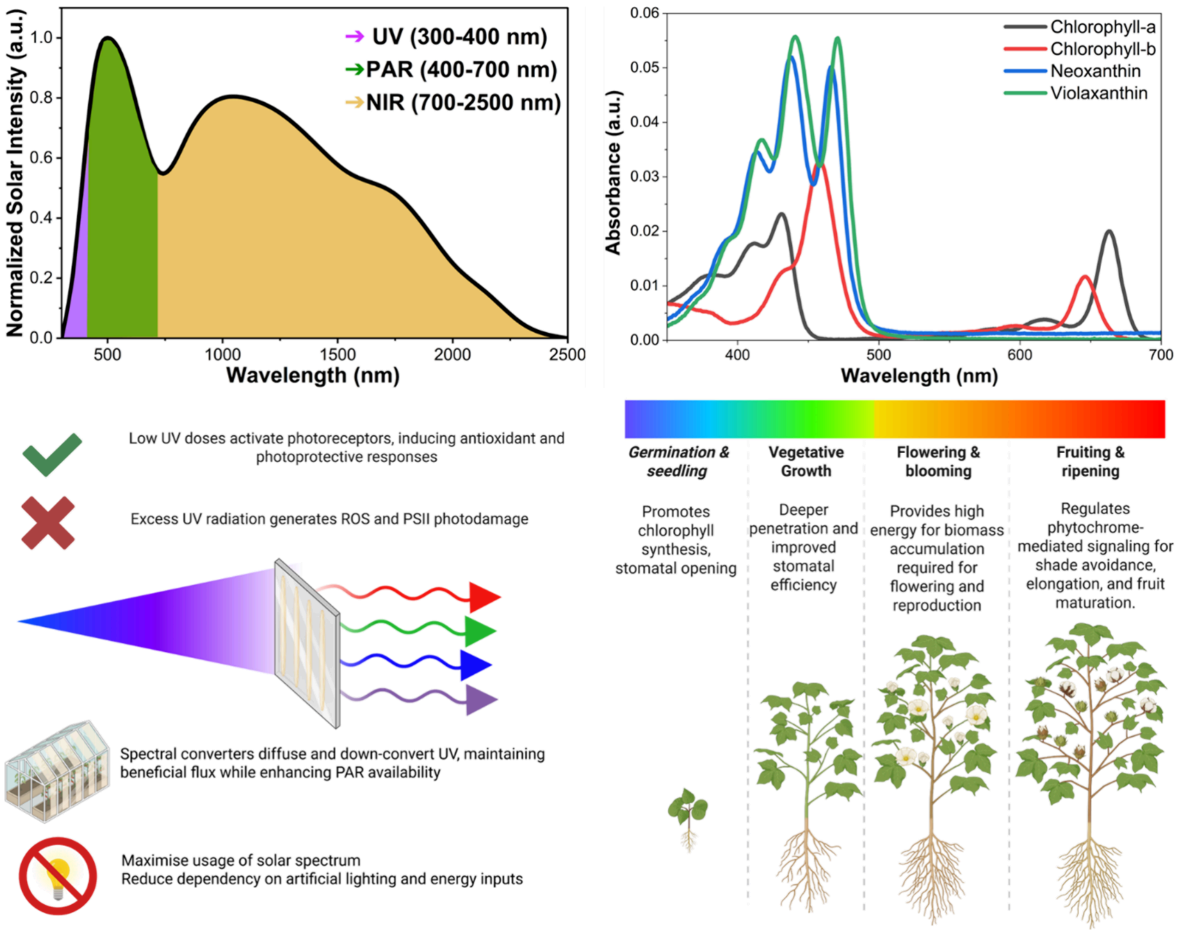

Figure 2. (Top left) Normalized solar spectrum at sea level, illustrating that only a fraction of solar energy falls within the photosynthetically active radiation (PAR, 400−700 nm) range. (Top right) Absorbance spectra of major photosynthetic pigments, including chlorophyll and carotenoids, highlighting their strong absorption in the blue and red regions but poor absorption in the green region. (Bottom left) Conceptual diagram highlighting the benefits of UV-diffusion in agriculture. (Bottom right) The distinct roles of different PAR wavelengths throughout the plant life cycle.

equivalent; they play distinct and synergistic roles in regulating plant growth, development, and metabolism (Figure 2).

Red light (600−700 nm) is widely recognized as the most efficient wavelength range for driving CO_2 assimilation. The quantum yield of photosynthesis, a measure of CO_2 fixed per photon absorbed, peaks in the orange-red region, around 610−650 nm.[5] This high efficiency is directly linked to the strong absorption in this region by chlorophyll a and chlorophyll b, the primary photosynthetic pigments (Figure 2). Blue light (400−500 nm), while also strongly absorbed by chlorophylls and carotenoids (Figure 2), is generally used less efficiently for CO_2 assimilation on a per-photon basis compared to red light.[6] However, its role in plant development is indispensable. Blue light is the primary energy source for phototropic responses (plants bending toward light) and is a key regulator of stomatal opening, which governs gas exchange. Studies have shown that red light enhances CO_2 fixation and chlorophyll accumulation, whereas blue light regulates stomatal traits.[7,8] Recent studies have also demonstrated the influence far-red light has on stomatal behavior and phytochrome morphology[9]. Therefore, balanced ratio of red to blue light is crucial for achieving both high photosynthetic rates and healthy plant morphology.[10]

For decades, green light was dismissed as being largely unusable for photosynthesis, simply because it is poorly absorbed by chlorophyll and is thus reflected, giving leaves their characteristic color. While the quantum yield of green light is lower than red light at the single-leaf, low-intensity level, its poor absorption becomes a critical advantage in more complex, realistic scenarios. Because red and blue light are absorbed so strongly, they are captured almost entirely by the uppermost cell layers of a leaf. At high light intensities, this can lead to saturation of the photosynthetic machinery in these layers, where excess energy is wasted as heat and can even cause photoinhibitory damage.[6] Green light, by contrast, can penetrate much deeper into the leaf mesophyll and further down into the plant canopy. This allows it to excite chloroplasts in lower tissue layers that would otherwise be light-starved, thereby increasing the overall photosynthetic efficiency of the entire leaf and canopy, particularly under high-light conditions, by improving stomatal efficiency[11] and antioxidative enzyme activity.[12]

2.2. Ultraviolet Radiation: Stress and Signaling

The ultraviolet (UV) portion of the solar spectrum, which accounts for 8% of incident solar energy (Figure 2), represents both a threat and a regulatory signal for plants. Among UV wavelengths, UV−B (280−315 nm) is the most biologically impactful.

2.2.1. Damage. UV−B photons are absorbed by aromatic amino acids within the D1 and D2 proteins of Photosystem II (PSII), leading to photo-oxidative degradation of the D1 protein, a critical event in PSII photoinhibition.[13−15] In parallel, UV−B exposure generates reactive oxygen species (ROS), which indiscriminately oxidize biomolecules as they cause lipid peroxidation that disrupts thylakoid and chloroplast membranes, denature enzymes, and induce DNA lesions.[16] Together, these processes compromise both the structural and functional integrity of the photosynthetic apparatus.[17]

2.2.2. Defense. To counteract these stresses, plants activate multiple protective mechanisms. They accumulate UV-absorbing flavonoids in epidermal tissues, which act as sunscreens; they employ DNA repair enzymes (photolyases) to reverse UV-induced pyrimidine dimers; and they trigger photomorphogenic signaling through the UVR8 photoreceptor, which mediates protective gene expression.[18,19]

2.2.3. Hormetic Effect. Interestingly, UV−B is not solely detrimental. At low doses, it functions as a signaling cue that primes antioxidant responses, enhances secondary metabolite production, and improves stress resilience.[20] At high doses, however, these benefits are outweighed by PSII photodamage and oxidative stress, resulting in growth inhibition.

Agricultural strategies must therefore be nuanced. Complete exclusion of UV radiation could suppress valuable acclimatory signaling, while excess exposure is damaging. The optimal approach may involve attenuating UV−B to subdamaging levels while allowing sufficient flux for signaling or employing photonic augmentation technologies that convert surplus UV light into photosynthetically active radiation, while enhancing the plant's intrinsic antioxidant defenses.

3. EXTERNAL LIGHT MODULATION VIA SOLID-STATE FLUORESCENCE

3.1. Principles of Spectral Conversion

Solid-state fluorescence (also called photonic down-conversion) involves materials that absorb high-energy photons (UV, blue) and re-emit them at longer wavelengths, in this case the PAR region. Greenhouses in agriculture already play a vital role in contributing to largely reduced water consumption and therefore refining resource use.[21] Agricultural films and greenhouse panels doped with down-converting materials can both protect plants from damaging UV and recycle photons into PAR. This is a similar concept to Luminescent Solar Concentrators (LSCs), which are being developed for agrivoltaics. In an LSC, a transparent waveguide (e.g., a glass or polymer panel) is doped with a luminescent material. Incident sunlight is absorbed by the material, re-emitted, and then trapped within the waveguide by total internal reflection until it reaches solar cells mounted at the edges.[22]

3.2. Agricultural Films and Coatings

Before considering wavelength-shifting and luminescent technologies, it is important to note that most of the global greenhouse cultivation still relies on conventional polymeric films. Energy consumption and conversion efficiency has been improved on in more advanced greenhouses, thus reducing any impact of their environmental footprint in addition to land use.[23] Industry leaders such as Plastika Kritis, Berry Global, and ExxonMobil manufacture multilayer films composed primarily of polyethylene (PE), ethylene-vinyl acetate (EVA), and thermoplastic polyolefins (TPO). These films are typically engineered with a combination of UV stabilizers, thermal additives, and light-diffusing agents. For example, Plastika Kritis' Suncooler incorporates near-infrared (NIR) additives to lower canopy heat load, while its Polydispersive line integrates nanoadditives for ultrahigh haze with minimal loss of transmission.[24] Berry Global's multilayer greenhouse covers, such as the Super4 film, blend LDPE/EVA/TPO to provide high optical clarity, thermal retention, and pollinator compatibility, with recent expansions into biobased PE films for sustainability.[25]

While these polymer films are highly effective at managing thermal balance, extending film lifetimes, and improving light diffusion, they are inherently monodimensional solutions. Their function is limited to modifying light intensity and thermal load, without altering the spectral composition of incoming radiation. As a result, their utility is strongly climate-dependent.In hot and arid regions, films with NIR-blocking or cooling properties reduce heat stress, whereas in temperate or low-light climates, maximizing transmission and diffusion is preferred. However, these materials cannot actively convert non-PAR photons into photosynthetically useful wavelengths, meaning they do not fundamentally expand the usable solar spectrum. This gap has motivated the development of fluorescent and luminescent films that go beyond modulation to deliver true spectral conversion.

Early efforts to enhance the spectral quality of light in agriculture focused on material classes with strong luminescent properties. Among the first materials tested were organic dyes, such as rhodamines and coumarins, which offered high quantum yields for down-conversion. However, their long-

Table 1. Commercial and Academic Developments in Luminescent Agricultural Films and Coatings

name and material type	mechanism	reported Impact
quantum-dot coatings, Sinbiosys[32]	UV → red/orange + UV diffusion	improved canopy uniformity and early growth
nanoparticle coating, Fotoniq[33]	UV → PAR conversion	1.7–3% ↑ yield
quantum dot films, UbiGro[34]	UV → red/orange	20–30% yield ↑
luminescent spray coatings, Lambda Energy/Agri[35]	UV → PAR down-conversion	9% ↑ basil yield, 30% ↑ rocket biomass
luminescent spectral-shifting films (dye-based), LLEAF[36]	green → red	20% ↑ growth rate and 10–35% ↑ in crop yields
photoconversion films, Cascade[37]	UV → blue Green → red	↑ yield by 13–14.5% and 15.7% in raspberries and tomatoes respectively
micro cone arrays with Lumogen Red[38]	Green → red	86% ↑ in incident red light
PMMA or cellulose acetate films with Lumogen Red[39]	Green → red	+20–30% ↑ in biomass of *Lactuca sativa*
$CuInS_2/ZnS$ quantum dot films[30]	UV/blue → red (600 and 660 nm)	At 600 and 660 nm emission ↑ in dry mass (13 and 9%), total leaf area (8 and 13%)
PMMA films with Eu-polyoxotitanates complexes[40]	UV→ red	9% ↑ in dry mass
polyolefin-type film with Eu-triphenylphosphineoxide[41]	UV→ red	↑ 1.2- and 1.4-fold for plant height and biomass respectively

term viability was limited by poor photostability under sunlight, high production costs, and environmental risks from leaching.[26] Subsequently, attention turned to rare-earth complexes. Lanthanide-based emitters, particularly Eu^{3+} and Tb^{3+} complexes, were attractive for their narrow-band, highly efficient emission in the red part of the spectrum (612–615 nm), which aligns closely with chlorophyll absorption peaks.[27,28] Despite this advantage, their widespread use has been constrained by high costs, potential quenching effects, and relatively short lifetimes within polymer matrices.[29,22]

Another important class of materials includes inorganic phosphors, such as Eu^{2+} silicates, Ce^{3+} oxides, or Mn^{4+} sulfides, which provide high luminous efficiency, strong thermal and chemical stability, and long lifetimes. These can be used to convert UV into blue light or blue-green into far-red, thereby targeting phytochrome responses.[29] The primary technical challenge with phosphors is achieving uniform dispersion in a polymer film or coating without increasing light scattering and lowering overall transmittance. More recently, a highly versatile approach has emerged with the use of metal quantum dots (MQDs), which are semiconductor nanocrystals whose emission color can be tuned by controlling their size. MQDs possess broad absorption spectra, high quantum yields, and good photostability, offering exceptional flexibility for designing custom light spectra. While materials such as cadmium-based QDs have been extensively studied, concerns over heavy metal toxicity have shifted focus toward more benign alternatives like silicon, graphene, or carbon QDs for agricultural applications.[30,31]

Despite them taking up a large section of the solar spectrum (Figure 2), converting near-infrared wavelengths into PAR would require photon up conversion, which involves the absorption of multiple low-energy photons to emit a higher-energy photon. Such processes are extremely inefficient. This is why most technologies focus on inefficiently utilized UV or Green light to down convert to photosynthetically active emissions in the blue and red. Recent years have seen a wave of companies and academic spin-offs bringing luminescent photonic materials from lab benches to greenhouse panels, each demonstrating tangible plant productivity benefits (Table 1).

4. INTERNAL AUGMENTATION VIA PLANT NANOBIONICS

4.1. Concept and Rationale

Plant nanobionics introduces engineered nanomaterials into living tissues, where they act as artificial antennae to extend light absorption beyond the natural limits of plants' light harvesting antennae. Natural photosynthesis is saturated by as little as 10% of full sunlight, and the antenna complexes are blind to large portions of the solar spectrum (Figure 2), particularly in the UV and near-infrared regions.[42] Nanomaterials, such as carbon nano assemblies and metallic quantum dots, can be engineered to absorb strongly in these very regions. Once excited by these otherwise wasted photons, the nanomaterial can transfer the captured energy to the nearby chlorophyll molecules of Photosystem I (PSI) or Photosystem II (PSII). This effectively broadens the plant's usable light spectrum, increasing the total number of excitons delivered to the reaction centers and thereby boosting the rate of electron transport and carbon fixation. This approach transforms the plant into a living hybrid bionic device, transferring more energy to the photosystems, potentially through the FRET mechanism and direct electron transfer.

4.2. Uptake, Transport, and Localization

Plants present two primary portals for nanomaterial entry, their foliar surfaces and roots. Spraying nanomaterial suspensions onto leaves enables uptake through natural foliar openings such as stomata and hydathodes, as well as through microcracks in the cuticle (Figure 1). Particle size is critical, as smaller nanomaterials can more readily penetrate cell walls and membranes, improving uptake efficiency.[43] Alternatively, nanomaterials that are introduced into soil or hydroponic media are absorbed by roots and transported via two pathways:[44] the apoplastic route (movement through cell wall spaces) and the symplastic route (movement through the cytoplasm and plasmodesmata) (Figure 1). Once internalized, nanomaterials enter the vascular system for long-distance transport.

Systemic distribution occurs primarily through the xylem, which carries nanomaterials upward with the transpiration stream, and the phloem, which redistributes them with food and nutrients to different parts of the plant. Importantly,

https://doi.org/10.1021/acsagscitech.5c00975

nanomaterial's surface charge strongly influences mobility. Negatively charged nanomaterials exhibit reduced adhesion to the negatively charged xylem walls and lower aggregation with other particles. This electrostatic "non-stick effect" maintains dispersion in the transpiration stream, promoting efficient systemic transport from the roots to the leaves.[45] For nanomaterial uptake in plants, ICP-MS, isotope labeling, and confocal imaging are widely applied to confirm and quantify translocation.[46]

4.3. Förster Resonance Energy Transfer (FRET)

FRET is hypothesized as a central mechanism by which nanomaterials enhance photosynthesis. FRET is a quantum mechanical phenomenon based on dipole−dipole coupling. An excited donor molecule can transfer its energy to a nearby acceptor molecule without the emission and subsequent reabsorption of a photon[47] (Figure 3). For FRET to occur efficiently, two main conditions must be met. First, the emission spectrum of the donor molecule must significantly overlap with the absorption spectrum of the acceptor molecule, and second, the donor and acceptor must be in very close proximity, typically between 1 and 10 nm.[48] In the context of plant nanobionics, the fluorescent nanomaterial serves as the donor, and a native chlorophyll molecule in a light-harvesting complex serves as the acceptor. Existing evidence of the FRET mechanism, is indirect, based on spectral overlap and isolated chloroplast photophysics. The definitive confirmation of FRET requires more advanced spectroscopic techniques, particularly Fluorescence Lifetime Imaging Microscopy (FLIM),[42] to show decreased donor lifetimes consistent with the FRET mechanism. We therefore present FRET as a promising but currently unvalidated hypothesis.

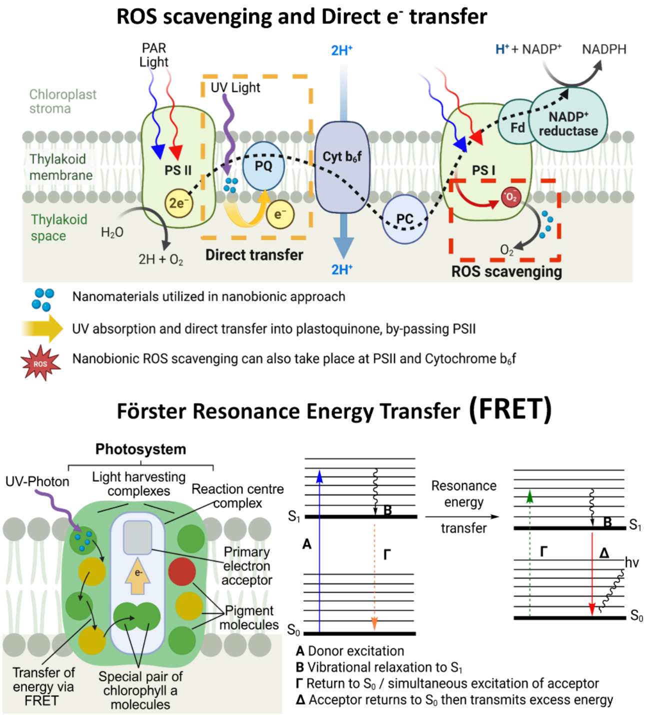

Figure 3. Proposed molecular mechanisms for photosynthetic augmentation by internal nanobionic agents. (Top) Z-scheme of the electron transport chain, displaying direct electron transfer and ROS scavenging. (Bottom left) Nanomaterials acting as artificial plant antennae via the FRET mechanism, with the corresponding Jablonski diagram (bottom right).

4.4. Alternative and Complementary Mechanisms

While FRET is a leading hypothesis, it is likely not the only light harvesting mechanism through which nanomaterials can enhance photosynthesis. Two other plausible pathways, which may act in concert with FRET, are direct electron transfer and redox modulation.

In the case of direct electron transfer, instead of transferring energy via FRET, an excited nanomaterial could act as an electron donor, directly injecting a high-energy electron into the photosynthetic electron transport chain.[49] The mobile electron carrier plastoquinone (PQ), which shuttles electrons from PSII to the Cytochrome b_6f complex, has been identified as a likely target for this process (Figure 3). This mechanism would be particularly beneficial under conditions where PSII is damaged or rate-limiting, such as under high light or UV stress.

The second pathway involves redox homeostasis. Some nanomaterials possess intrinsic redox activity that can indirectly benefit photosynthesis by mitigating oxidative stress (Figure 3). Redox-active materials like nanoceria can act as catalytic ROS scavengers, neutralizing the harmful byproducts of excess light absorption. It is likely that the most effective nanobionic agents employ a combination of these mechanisms, enhanced light absorption (via FRET or direct electron transfer) and enhanced photoprotection (via ROS scavenging), to achieve a synergistic improvement in photosynthetic performance.

5. NANOBIONIC AGENTS

5.1. Carbon Nanoassemblies

The term carbon nanoassemblies is employed in this review as a broader designation encompassing carbon-based nanomaterials such as carbon and graphene quantum dots. Unlike

Table 2. Efficacy of Carbon Nanoassemblies in Enhancing Plant Growth and Photosynthesis[a]

plant species	application method	key findings & reported benefits
Malus domestica (Apple)[49]	foliar spray	↑ 24.3% photosynthetic efficiency, ↑ 11.4% soluble sugar; mechanism via electron transfer to plastoquinone pool.
Arabidopsis thaliana[50]	foliar spray	↑ 1.8-fold fresh weight; enhanced activities of PSI & PSII, accelerated electron transport.
Arabidopsis thaliana and *Trifolium repens* L. (White Clover[53])	root infiltration	↑ 20% grain production
Solanum lycopersicum (Tomato) and *Zea mays* (Corn) seedlings[54]	root infiltration	↑ 92.4% and 76.2% to tomato and corn germination rates
Vigna radiata (Mung bean) seedlings[55]	root infiltration	↑ 66.3% increase to chlorophyll content at 750 mg/L

[a] The table summarizes key findings from recent studies, detailing improvements in biomass, photosynthetic efficiency, and germination rates across different species and application methods.

metallic quantum dots, which exhibit emission properties governed by quantum confinement effects, carbon nanomaterials display photoluminescence primarily through surface states and molecular emissive domains. As such, describing them strictly as "dots" can be misleading, and the term nanoassemblies better reflects their heterogeneous structural and optical characteristics. These carbon nanoassemblies have emerged as a leading platform for plant nanobionics due to their low toxicity, biodegradability, photostability, and scalable synthesis from inexpensive precursors. Recent research has demonstrated the remarkable efficacy of these materials in enhancing photosynthesis and boosting crop yields across a wide variety of plant species. As summarized in Table 2, the application of carbon-based nanomaterials has led to substantial gains in agricultural productivity. The physiological basis for these improvements lies in the ability of carbon dots to function as both light converters and photosensitizers.[50] As light converters, they can absorb underutilized high-energy UV radiation and re-emit it as photosynthetically active light, whereas, as photosensitizers, they directly participate in the photosynthetic electron transport chain. Upon excitation, carbon nanoassemblies can inject high-energy electrons into the electron transport chain, accelerating the overall rate of electron flow and subsequent ATP and NADPH production.[51] In parallel, carbon nanoassemblies may also enhance photosynthesis via the FRET mechanism, where their emission energy is nonradiatively transferred to nearby chlorophyll molecules, increasing excitation of Photosystems I and II without direct charge transfer.[52]

The key advantage of using undoped carbon-based systems is their inherent biocompatibility, which circumvents the dose-dependent cytotoxicity often associated with metal-based nanoparticles.[51] While high concentrations of graphene quantum dots have been shown to induce oxidative stress[55], the toxicity threshold is generally much higher than for their metallic counterparts. Furthermore, the ability to synthesize carbon nanoassemblies from abundant and renewable biomass makes them a cost-effective and environmentally sustainable choice for large-scale agricultural use. This scalability has already been demonstrated by companies such as Glaia (UK), which markets a carbon-based biostimulant that has delivered yield increases of up to 25% in lettuce and 21% in strawberries in field trials, and QarboTech (Malaysia), whose biomass-derived carbon nanomaterial spray (QarboGrow) has reported 10−50% yield gains in rice and high-value horticultural crops.[56,57]

5.2. Metal-Doped Carbon Nanoassemblies

The introduction of metal heteroatoms into carbon nanoassemblies modifies the electronic structure by altering the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) levels, narrowing the band gap and creating intermediate states that facilitate charge transfer.[58] In addition, metal atoms introduce catalytically active centers and structural defects that enhance conductivity and redox reactivity in carbon nanoassemblies, by providing accessible electron-delocalization pathways and promoting charge-transfer kinetics.[59,60] This dual effect transforms these metal-doped carbon nanoassemblies, enabling them to directly engage in photosynthetic and metabolic processes. The usage of magnesium doped carbon nano assemblies in rice seedlings increased the fresh biomass by 71%, while also displaying a 52% and 47% increase in photosynthetic and RuBisCO activity respectively[61]. Furthermore, the introduction of Zn into carbon nano assemblies, improved the grain yield in wheat by 16% while also improving the total zinc and nitrogen content in the crop by 19 and 118% respectively.[62] By embedding these metals within carbon nanoassemblies, researchers achieve not only higher quantum yields for light conversion but also the codelivery of essential micronutrients to plants. This multifunctionality highlights the dual promise of metal-doped CDs: improved photonic efficiency at the chloroplast level and enhanced nutritional outcomes at the whole-plant and crop-product level.

5.3. Metal-Based Nanomaterials

To fully appreciate the unique capabilities of metal-doped carbon nanoassemblies, it is useful to compare them with other classes of metal-based nanomaterials applied in photosynthetic augmentation. While effective, these systems typically operate through indirect or extracellular mechanisms, in contrast to the intracellular, biocatalytic roles of carbon nanoassemblies. For instance, plasmonic gold and silver nanoparticles enhance photosynthesis via Localized Surface Plasmon Resonance (LSPR), which amplifies the local electromagnetic field near the nanoparticle surface. This field increases the photon absorption rate of nearby chlorophylls, boosting excitation without direct entry into the chloroplast or electron donation to the electron transport chain. This was investigated in a recent study on Chinese mustard (*Brassica juncea*) that displayed how gold nanoparticles can boost photosynthesis and nitrogen assimilation.[63]

In contrast, metal oxide nanoparticles (TiO_2, ZnO, CuO) function more as biochemical regulators than direct photonic enhancers. TiO_2 can improve photosynthetic efficiency,[64] while ZnO nanoparticles up-regulate chlorophyll biosynthesis[65] and photosynthetic efficiency,[66] while reducing lipid peroxidation.[67] Their effects are systemic, often improving stress tolerance and enzyme efficiency rather than directly integrating into the photosystems. While metal-doped carbon nanoassemblies penetrate chloroplasts, engage directly with the photosynthetic electron transport chain, and simultaneously deliver essential micronutrients, metallic nanoparticles typically act through external light field effects (plasmonics) or metabolic regulation (metal oxides). Thus, doped carbon nanoassemblies represent a stronger nanobionic candidate compared to the broader-acting metal nanomaterials.

6. COMPARATIVE ANALYSIS: NANOBIONICS VS SOLID-STATE FLUORESCENCE

6.1. Advantages of the Direct and Indirect Approaches

Plant nanobionics offers several distinct advantages as a direct approach to photosynthetic augmentation. By delivering energy directly to the photosynthetic reaction centers, this strategy minimizes losses associated with reflection and transmission at the leaf surface, thereby increasing photosynthetic efficiency. Once internalized and translocated, nanomaterials can exert systemic and persistent effects, sustaining enhanced photosynthetic activity throughout the lifetime of the plant tissue without requiring repeated external applications. Moreover, nanomaterials are inherently multifunctional. They can be engineered not only to broaden light harvesting but also to deliver essential micronutrients such as copper and zinc, to mitigate abiotic stress through reactive oxygen species scavenging (e.g., nanoceria), or even to function as nanosensors of plant health.[68]

On the other hand, wavelength-shifting materials provide a more scalable and noninvasive strategy for photosynthetic augmentation. Since they act externally, they do not require nanomaterials to cross biological barriers, thereby avoiding the complexities and potential toxicities associated with uptake, translocation, and bioaccumulation. This external mode of action also simplifies regulatory approval, as films and coatings are generally considered safer and more straightforward to license compared to technologies that introduce engineered nanomaterials into the food chain. Furthermore, luminescent films can be readily integrated with existing greenhouse infrastructure and are compatible with agrivoltaic systems such as luminescent solar concentrators, enabling the dual benefits of enhanced crop productivity and electricity generation.

6.2. Material Limitations

Nanobionics face major challenges in achieving controlled delivery to chloroplasts, avoiding dose-dependent phytotoxicity, and ensuring safe long-term environmental fate within soils and food webs.[69] Wavelength-shifting films, in contrast, are limited by photodegradation, reduced light transmittance if not optimally designed, and confinement to greenhouse or semicontrolled environments rather than open-field agriculture.

A critical knowledge gap remains in the mechanistic validation of nanobionics. There is still no direct, unequivocal proof of FRET between artificial nanoantennae and chlorophyll within living chloroplasts. Current evidence of spectral overlap and spatial colocalization remains circumstantial. The decisive next step is the adoption of Fluorescence Lifetime Imaging Microscopy in all nanobionic studies utilizing light harvesting properties, which can map fluorescence lifetimes in situ and reveal the shortened donor lifetimes diagnostic of FRET in isolated chloroplast trials or cyanobacteria.[70] Moving from steady-state to time-resolved imaging would provide the definitive mechanistic proof needed for rational nanoantenna design, while single-molecule approaches could later refine efficiency measurements.[71,72]

6.3. Ecological, Safety, and Scalability Implications

A significant hurdle for both technologies is the lack of comprehensive understanding of their long-term environmental impact. For nanobionics, critical questions remain about the fate of nanomaterials after the plant is harvested or decomposes.[73] Do they persist in soils, alter microbial community composition, disrupt nutrient cycling, or enter food chains through trophic transfer. Studies highlight that the transport and toxicity data emphasizes that particle size, surface coating, aggregation state, and dissolution behavior are the principal controls on mobility and bioavailability in soil plant systems.[74] The propensity for accumulation depends on (i) the stability of the, (ii) dissolution into ionic species, and (iii) the developmental timing of exposure.[75] Therefore, accumulation patterns are highly material- and species-dependent. For example, cerium oxide nanoparticles (CeO_2−NPs) applied to soil have been detected in lettuce tissues and can undergo biotransformation, with concentration-dependent effects on plant physiology,[76] while silver nanoparticles have been reported to penetrate tomato roots and accumulate in vegetative tissues[77] Furthermore, in carbo nano assemblies, studies consistently report low cytotoxicity, high biodegradability with a minimal aggregation in plant tissues.[53,78]

Analytical strategies for evaluating nanomaterial uptake and translocation must balance mechanistic resolution with scalability. For carbon nanoassemblies, high-precision methods such as isotope labeling could, in principle, distinguish internalized CNAs from native plant carbon pools and map their movement within tissues; however, these approaches are not feasible at agricultural scale. Instead, for carbon-based systems, the downstream physiological and biochemical impact of treatment can be more realistically assessed through metabolomic profiling, which enables high-throughput detection of shifts in central metabolism, redox balance, and secondary metabolites associated with nanomaterial activity. For inorganic nanomaterials and metal-doped CNAs, scalable elemental analyses are more straightforward. Techniques such as ICP-MS, supported by autosamplers, allow hundreds of plant digests to be processed in a single run, providing quantitative information on elemental loading across large experimental cohorts. Additionally, portable XRF instruments offer a practical field-deployable option for semiquantitative screening of metal accumulation directly in leaves, stems, or soils, enabling rapid in situ monitoring without destructive sampling.

On the other hand, for agricultural films and composites, the degradation products of both the polymer matrix and the luminescent materials must be assessed for their potential ecotoxicity and persistence in the environment.[79] Rigorous, long-term life cycle assessments under realistic field conditions are urgently needed to ensure these technologies are not only effective but also environmentally benign. Equally critical is scalability and farmer adoption. One way to improve large scale deployment of the indirect light harvesting approach is the combination with luminescent solar concentrators. When integrated with the indirect approach, LSCs offer a dual-use advantage as they can concurrently (i) optimize the spectral quality of light reaching crops by converting UV into PAR wavelengths, and (ii) generate electrical power from the guided photons without significantly shading the crop canopy. This would also provide producers with the financial incentive to consider investing in this new technology.

Although many of the nanomaterials and luminescent complexes can, in principle, be synthesized from low-cost precursors, transitioning from laboratory-scale syntheses to industrial manufacturing, while maintain consistent nanomaterial sizes and quantum yields remains a challenge. The economics of synthesis, purification, formulation, and delivery must ultimately be weighed against yield gains to establish clear cost−benefit outcomes. Without demonstrated scalability, even the most promising technologies will remain confined to research settings rather than delivering real-world agricultural impact.

Nanobionics and solid-state fluorescence represent promising strategies to address the spectral limitations of photosynthesis, offering direct and indirect routes to enhance light-use efficiency in crops. However, their translation beyond proof-of-concept studies will depend on rigorous mechanistic validation, particularly for proposed energy-transfer pathways, alongside comprehensive assessments of environmental fate, food safety, and long-term ecological impact. Ultimately, scalable manufacturing, realistic field trials, and clear cost−benefit advantages for growers will determine whether these photonic augmentation technologies can progress from laboratory demonstrations to practical agricultural solutions.

https://doi.org/10.1021/acsagscitech.5c00975

AUTHOR INFORMATION

Corresponding Author

Ming Xie − *Department of Chemical Engineering, University of Bath, Bath BA2 7AY, U.K.*; orcid.org/0000-0003-2729-9746; Email: mx406@bath.ac.uk

Authors

Konstantinos T. Kotoulas − *Department of Chemical Engineering and Department of Chemistry, University of Bath, Bath BA2 7AY, U.K.; School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, U.K.*; orcid.org/0000-0001-9070-2054

Andrew D. Burrows − *Department of Chemistry, University of Bath, Bath BA2 7AY, U.K.*; orcid.org/0000-0002-9268-4408

Gareth Cave − *School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, U.K.*; orcid.org/0000-0002-4167-1332

Complete contact information is available at: https://pubs.acs.org/10.1021/acsagscitech.5c00975

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the funding support by the Leverhulme Trust (RPG-2022-277). Financial support from the Royal Society of Chemistry (grant number C23-4364412079) is also gratefully acknowledged. The authors also acknowledge financial support from the Royal Society International Exchange (IEC\NSFC\242089). Figures were created using BioRender.com.

REFERENCES

(1) Long, S. P.; Marshall-Colon, A.; Zhu, X. G. Meeting the Global Food Demand of the Future by Engineering Crop Photosynthesis and Yield Potential. *Cell Press* **2015**, *161*, 56−66.

(2) Zhu, X. G.; Long, S. P.; Ort, D. R. Improving Photosynthetic Efficiency for Greater Yield. *Annual Review of Plant Biology* **2010**, *61*, 235−261.

(3) Cotton, C. A. R.; Douglass, J. S.; De Causmaecker, S.; Brinkert, K.; Cardona, T.; Fantuzzi, A.; Rutherford, A. W.; Murray, J. W. Photosynthetic Constraints on Fuel from Microbes. *Front. Bioeng. Biotechnol.* **2015**, 36.

(4) Hogewoning, S. W.; Wientjes, E.; Douwstra, P.; Trouwborst, G.; van Ieperen, W.; Croce, R.; Harbinson, J. Photosynthetic Quantum Yield Dynamics: From Photosystems to Leaves. *Plant Cell* **2012**, *24*, 1921−1935.

(5) Barnes, C.; Tibbitts, T.; Sager, J.; Deitzer, G.; Bubenheim, D.; Koerner, G.; Bugbee, B. Accuracy of Quantum Sensors Measuring Yield Photon Flux and Photosynthetic Photon Flux. *HortScience* **1993**, *28*, 1197−1200.

(6) Liu, J.; van Iersel, M. W. Photosynthetic Physiology of Blue, Green, and Red Light: Light Intensity Effects and Underlying Mechanisms. *Front. Plant Sci.* **2021**, *12*, No. 619987.

(7) Zhao, S.; Li, X.; Kang, Y.; Lin, Y.; Wu, Y.; Yang, Z. Photomorphogenesis and Photosynthetic Trait Changes in Melon Seedlings Responding to Red and Blue Light. *Horticulturae* **2024**, *10*, 961.

(8) Nguyen, T. A. H.; Thuong, K. D.; Trang, V. B. The Effects of Blue and Red Light on the Hill Reaction of Isolated Chloroplasts, Photosynthesis and Saponin Accumulation in Fenugreek Leaves (Trigonella Foenum-Graecum L.). *Res. J. Biotechnol.* **2023**, *18*, 74−81.

(9) Park, J. U.; An, S. K.; Kim, J. Far-Red Light Affects Stomatal Opening and Evapotranspiration of Sweet Basil. *Horticulturae* **2023**, *9*, 1095.

(10) Li, X.; Zhao, S.; Lin, A.; Yang, Y.; Zhang, G.; Xu, P.; Wu, Y.; Yang, Z. Effect of Different Ratios of Red and Blue Light on Maximum Stomatal Conductance and Response Rate of Cucumber Seedling Leaves. *Agronomy* **2023**, *13*, 1941.

(11) Bian, Z.; Zhang, X.; Wang, Y.; Lu, C. Improving Drought Tolerance by Altering the Photosynthetic Rate and Stomatal Aperture via Green Light in Tomato (Solanum Lycopersicum L.) Seedlings under Drought Conditions. *Environ. Exp. Bot.* **2019**, *167*, No. 103844.

(12) Bian, Z.; Yang, Q.; Li, T.; Cheng, R.; Barnett, Y.; Lu, C. Study of the Beneficial Effects of Green Light on Lettuce Grown under Short-Term Continuous Red and Blue Light-Emitting Diodes. *Physiologia Plantarum* **2018**, *164*, 226−240.

(13) Wilson, M. I.; Greenberg, B. M. Protection of the D1 photosystem II reaction center protein from degradation in ultraviolet radiation following adaptation of Brassica Napus L. to growth in Ultraviolet-B. *Photochem. Photobiol.* **1993**, *57*, 556−563.

(14) Bouchard, J. N.; Roy, S.; Campbell, D. A. UVB effects on the photosystem II-D1 protein of phytoplankton and natural phytoplankton communities. *Photochem. Photobiol.* **2006**, *82*, 936−951.

(15) Booij-James, I. S.; Dube, S. K.; Jansen, M. A.; Edelman, M.; Mattoo, A. K. Ultraviolet-B Radiation Impacts Light-Mediated Turnover of the Photosystem II Reaction Center Heterodimer in Arabidopsis Mutants Altered in Phenolic Metabolism. *Plant Physiol.* **1994**, *124*, 1275−1284.

(16) Khan, I.; Sohail; Zaman, S.; Li, G.; Fu, M. Adaptive Responses of Plants to Light Stress: Mechanisms of Photoprotection and Acclimation. *Front. Plant Sci.* **2025**, No. 1550125.

(17) Shi, C.; Liu, H. How Plants Protect Themselves from Ultraviolet-B Radiation Stress. *Plant Physiology* **2021**, *187*, 1096−1103.

(18) Fraikin, G. Y. Signaling Mechanisms Regulating Diverse Plant Cell Responses to UVB Radiation. *Biochemistry* **2018**, *83*, 787−794.

(19) Asik, E.; Kashif, S. Z.; Oztas, O. Plant Tolerance Mechanisms to DNA-Damaging UV Stress. *J. Exp. Bot.* **2025**, *77*, 27.

(20) Chen, Z.; Dong, Y.; Huang, X. Plant Responses to UV-B Radiation: Signaling, Acclimation and Stress Tolerance. *Stress Biol.* **2022**, 51.

(21) Czyzyk, K. A.; Bement, T. S.; Dawson, W. F.; Mehta, K. Quantifying Water savings with greenhouse farming. In *Proceedings of the Fourth IEEE Global Humanitarian Technology Conference 2014*, San Jose/Silicon Valley: California USA, **2014**.

(22) Loh, K.; Harbick, K.; Eylands, N.; Kortshagen, U.; Ferry, V. Luminescent Solar Concentrator Greenhouses for Concurrent Energy Generation and Lettuce Production in the United States. In *AgriVoltaics Conference Proceedings*, **2025**; p 3.

(23) Ravishankar, E.; Booth, R. E.; Saravitz, C.; Sederoff, H.; Ade, H. W.; O'Connor, B. T. Achieving Net Zero Energy Greenhouses by Integrating Semitransparent Organic Solar Cells. *Joule* **2020**, *4*, 490−506.

(24) KRITIFIL Special agricultural films. *PLASTIKA KRITIS S.A. home page*. https://www.plastikakritis.com/en/kritifil-overview (accessed Nov 11, 2025).

(25) Luminance Tunnel Film. *AMCOR home page*. https://packagingsolutions.amcor.com/en/product/product-item/luminance-tunnel-film-13477127 (accessed Nov 11, 2025).

(26) Liu, Y.; Gui, Z.; Liu, J. Research Progress of Light Wavelength Conversion Materials and Their Applications in Functional Agricultural Films. *Polymers* **2022**, *14*, 851.

(27) Zhang, Z.; Li, Y.; Fu, Z.; Wang, D.; Wang, C.; Li, J. Ethyl Cellulose/Rare Earth Complexes Light-Conversion Films and Exploration in Acid Rain Detection. *Macromol. Mater. Eng.* **2022**, *307*, No. 2100630.

(28) Cho, C. T.; Bosco, G.; van der Kolk, E. The Potential of SiO2:Al3+,Eu2+ Blue Phosphor Coatings in Greenhouse Application. *Opt. Mater.* **2024**, *157*, No. 116047.

(29) Shabalina, A. V.; Kozlov, V. A.; Paskhin, M. O.; Popov, I. A.; Gudkov, S. V. A Mini-Review of Photoconversion Covers for Greenhouses: Assessment Parameters and Plant Experiment Results. *Horticulturae* **2025**, *11*, 680.

(30) 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.

(31) Hebert, D.; Boonekamp, J.; Parrish, C. H.; Ramasamy, K.; Makarov, N. S.; Castañeda, C.; Schuddebeurs, L.; McDaniel, H.; Bergren, M. R. Luminescent Quantum Dot Films Improve Light Use Efficiency and Crop Quality in Greenhouse Horticulture. *Front. Chem.* **2022**, *10*, No. 988227.

(32) Agriculture Luminescent Greenhouse Film. *SINBIOSYS home page*. https://www.sinbiosys.com/agricolture-luminescent-greenhouse-films/ (accessed Nov 11, 2025).

(33) PAR+ by FOTONIQ. *FOTONIQ home page*. https://www.fotoniq.com/par-product (accessed Nov 11, 2025).

(34) UbiGro Greenhouse films. *UbiGro home page*. https://ubigro.com/ (accessed Nov 11, 2025).

(35) Lamda agri, better light for plants. *LamdaEnergy home page*. https://www.lambda.energy/ (accessed Nov 11, 2025).

(36) Engineering for sunlight for increased productivity. *Lleaf home page*. https://lleaf.com/ (accessed Nov 11, 2025).

(37) Innovative agricultural films. *Light Cascade home page*. https://www.lightcascade.com/en/ (accessed Nov 11, 2025).

(38) Xu, Z.; Michalska, M.; Papakonstantinou, I. Optimizing Horticulture Luminescent Solar Concentrators via Enhanced Diffuse Emission Enabled by Micro-Cone Arrays. *ACS Applied Material Interfaces* **2024**, *16*, 27587−27595.

(39) 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. *Nature Food* **2021**, *2*, 434−441.

(40) Müller, R.; Okokhere-Edeghoghon, B.; Janowicz, N. J.; Bond, A. D.; Kociok-Kohn, G.; Cox, L. M. R.; Garzon, D.; Waine, T. W.; Truckell, I. G.; Gage, E.; Thompson, A. J.; Busko, D.; Howard, I. A.; Saavedra, M. S.; Richards, B. S.; Breiner, B.; Cameron, P.; Wright, D. S. Transparent, Sprayable Plastic Films for Luminescent Down-Shifted-Assisted Plant Growth. *Adv. Mater. Technol.* **2025**, *10*, No. 2400977.

(41) Shoji, S.; Saito, H.; Jitsuyama, Y.; Tomita, K.; Haoyang, Q.; Sakurai, Y.; Okazaki, Y.; Aikawa, K.; Konishi, Y.; Sasaki, K.; Fushimi, K.; Kitagawa, Y.; Suzuki, T.; Hasegawa, Y. Plant Growth Acceleration Using a Transparent Eu3+-Painted UV-to-Red Conversion Film. *Sci. Rep.* **2022**, *12*, 17155.

(42) Giraldo, J. P.; Landry, M. P.; Faltermeier, S. M.; McNicholas, T. P.; Iverson, N. M.; Boghossian, A. A.; Reuel, N. F.; Hilmer, A. J.; Sen, F.; Brew, J. A.; Strano, M. S. Plant Nanobionics Approach to Augment Photosynthesis and Biochemical Sensing. *Nat. Mater.* **2014**, *13*, 400−408.

(43) Avellan, A.; Yun, J.; Zhang, Y.; Spielman-Sun, E.; Unrine, J. M.; Thieme, J.; Li, J.; Lombi, E.; Bland, G.; Lowry, G. V. Nanoparticle Size and Coating Chemistry Control Foliar Uptake Pathways, Translocation, and Leaf-to-Rhizosphere Transport in Wheat. *ACS Nano* **2019**, *13*, 5291−5305.

(44) Sanzari, I.; Leone, A.; Ambrosone, A. Nanotechnology in Plant Science: To Make a Long Story Short. *Front. Bioeng. Biotechnol.* **2019**, *7*, 120.

(45) Feigl, G. The Impact of Copper Oxide Nanoparticles on Plant Growth: A Comprehensive Review. *J. Plant Interact.* **2023**, *18*, 1.

(46) Wojcieszek, J.; Jiménez-Lamana, J.; Ruzik, L.; Szpunar, J.; Jarosz, M. To-Do and Not-to-Do in Model Studies of the Uptake, Fate and Metabolism of Metal-Containing Nanoparticles in Plants. *Nanomaterials* **2020**, *10*, 1480.

(47) Müller, S. M.; Galliardt, H.; Schneider, J.; George Barisas, B.; Seidel, T. Quantification of Förster Resonance Energy Transfer by Monitoring Sensitized Emission in Living Plant Cells. *Front. Plant Sci.* **2013**, *4*, 413.

(48) Şener, M.; Strümpfer, J.; Hsin, J.; Chandler, D.; Scheuring, S.; Hunter, C. N.; Schulten, K. Förster Energy Transfer Theory as Reflected in the Structures of Photosynthetic Light-Harvesting Systems. *ChemPhysChem* **2011**, *12*, 518−531.

(49) Jing, X.; Liu, Y.; Liu, X.; Zhang, Y.; Wang, G.; Yang, F.; Zhang, Y.; Chang, D.; Zhang, Z. L.; You, C. X.; Zhang, S.; Wang, X. F. Enhanced Photosynthetic Efficiency by Nitrogen-Doped Carbon Dots via Plastoquinone-Involved Electron Transfer in Apple. *Hortic. Res.* **2024**, *11*, No. uhae016.

(50) Hu, H.; Cheng, W.; Wang, X.; Yang, Y.; Yu, X.; Ding, J.; Lin, Y.; Zhao, W.; Zhao, Q.; Ledesma-Amaro, R.; Chen, X.; Liu, J.; Yang, C.; Gao, X. Enhancing Plant Photosynthesis Using Carbon Dots as Light Converter and Photosensitizer. *BioRxiv* **2024**, 1.

(51) Chowmasundaram, Y. A. P.; Tan, T. L.; Nulit, R.; Jusoh, M.; Rashid, S. A. Recent Developments, Applications and Challenges for Carbon Quantum Dots as a Photosynthesis Enhancer in Agriculture. *RSC Adv.* **2023**, *13*, 25093−25117.

(52) Guirguis, A.; Yang, W.; Conlan, X. A.; Kong, L.; Cahill, D. M.; Wang, Y. Boosting Plant Photosynthesis with Carbon Dots: A Critical Review of Performance and Prospects. *Small* **2023**, No. e2300671.

(53) Li, H.; Huang, J.; Liu, Y.; Lu, F.; Zhong, J.; Wang, Y.; Li, S.; Lifshitz, Y.; Lee, S. T.; Kang, Z. Enhanced RuBisCO Activity and Promoted Dicotyledons Growth with Degradable Carbon Dots. *Nano Research* **2019**, *12*, 1585−1593.

(54) Chen, Q.; Ren, X.; Li, Y.; Liu, B.; Wang, X.; Tu, J.; Guo, Z.; Jin, G.; Min, G.; Ci, L. Promotion Effect of Nitrogen-Doped Functional Carbon Nanodots on the Early Growth Stage of Plants. *Oxford Mater. Sci.* **2020**, *1*, No. itab002.

(55) Feng, P.; Geng, B.; Cheng, Z.; Liao, X.; Pan, D.; Huang, J. Graphene Quantum Dots-Induced Physiological and Biochemical Responses in Mung Bean and Tomato Seedlings. *Revista Brasileira de Botanica* **2019**, *42*, 29−41.

(56) Microscopic improvements, monumental impact. *Glaia home page*. https://www.glaia.co.uk/ (accessed Nov 11, 2025).

(57) Photosynthesis enhancer. *Qarbotech home page*. https://qarbotech.com/ (accessed Nov 11, 2025).

(58) Sekar, R.; Basavegowda, N.; Jena, S.; Jayakodi, S.; Elumalai, P.; Chaitanyakumar, A.; Somu, P.; Baek, K. H. Recent Developments in Heteroatom/Metal-Doped Carbon Dot-Based Image-Guided Photodynamic Therapy for Cancer. *Pharmaceutics* **2022**, *14*, 1869.

(59) Gallareta-Olivares, G.; Rivas-Sanchez, A.; Cruz-Cruz, A.; Hussain, S. M.; González-González, R. B.; Cárdenas-Alcaide, M. F.; Iqbal, H. M. N.; Parra-Saldívar, R. Metal-Doped Carbon Dots as Robust Nanomaterials for the Monitoring and Degradation of Water Pollutants. *Chemosphere* **2023**, *312*, No. 137190.

(60) Mokoloko, L. L.; Forbes, R. P.; Coville, N. J. The Behavior of Carbon Dots in Catalytic Reactions. *Catalysts* **2023**, *13*, 1201.

(61) Li, Y.; Xu, X.; Lei, B.; Zhuang, J.; Zhang, X.; Hu, C.; Cui, J.; Liu, Y. Magnesium-Nitrogen Co-Doped Carbon Dots Enhance Plant Growth through Multifunctional Regulation in Photosynthesis. *Chem. Eng. J.* **2021**, *422*, No. 130114.

(62) Alikhani, M.; Mirbolook, A.; Sadeghi, J.; Lakzian, A. Effect of a New Slow-Release Zinc Fertilizer Based on Carbon Dots on the Zinc Concentration, Growth Indices, and Yield in Wheat (Triticum Aestivum). *Plant Physiol. Biochem.* **2023**, *200*, No. 107783.

(63) Khatoon, S.; Mahajan, M.; Kumari, S.; Iqbal, N.; Wahid, I.; Khan, M. I. R. Green-Synthesized Gold Nanoparticles Induce Adaptation in Photosynthetic Responses, Sugar and Nitrogen Metabolism, and Seed Yield of Salt-Stressed Mustard Plants. *Clean Technol. Environ. Policy* **2025**, *27*, 5683.

(64) Ze, Y.; Liu, C.; Wang, L.; Hong, M.; Hong, F. The Regulation of TiO2 Nanoparticles on the Expression of Light-Harvesting Complex II and Photosynthesis of Chloroplasts of Arabidopsis Thaliana. *Biological Trace Element Research* **2011**, *143*, 1131−1141.

(65) Geremew, A.; Carson, L.; Woldesenbet, S.; Wang, H.; Reeves, S.; Brooks, N.; Saganti, P.; Weerasooriya, A.; Peace, E. Effect of Zinc Oxide Nanoparticles Synthesized from Carya Illinoinensis Leaf Extract on Growth and Antioxidant Properties of Mustard (Brassica Juncea). *Front. Plant Sci.* **2023**, *14*, No. 1108186.

(66) Chen, H.; Song, Y.; Wang, Y.; Wang, H.; Ding, Z.; Fan, K. Zno Nanoparticles: Improving Photosynthesis, Shoot Development, and Phyllosphere Microbiome Composition in Tea Plants. *J. Nanobiotechnol.* **2024**, *22*, 389.

(67) Reddy Pullagurala, V. L.; Adisa, I. O.; Rawat, S.; Kalagara, S.; Hernandez-Viezcas, J. A.; Peralta-Videa, J. R.; Gardea-Torresdey, J. L. ZnO Nanoparticles Increase Photosynthetic Pigments and Decrease Lipid Peroxidation in Soil Grown Cilantro (Coriandrum Sativum). *Plant Physiology and Biochemistry* **2018**, *132*, 120−127.

(68) Kumar, K. M.; Nadaradjan, S.; Anand, M. S.; Premkumar, A.; Hemalatha, G. Enhancing Agricultural Sustainability through Plant Nanobionics: Innovations, Challenges and Future Directions. *International Journal of Research in Agronomy* **2024**, *7*, 251−259.

(69) Mittal, D.; Kaur, G.; Singh, P.; Yadav, K.; Ali, S. A. Nanoparticle-Based Sustainable Agriculture and Food Science: Recent Advances and Future Outlook. *Front. Nanotechnol.* **2020**, 2.

(70) Adília Lemos, M.; Sárniková, K.; Bot, F.; Anese, M.; Hungerford, G. Use of Time-Resolved Fluorescence to Monitor Bioactive Compounds in Plant Based Foodstuffs. *Biosensors* **2015**, *5*, 367−397.

(71) Broess, K.; Borst, J. W.; Van Amerongen, H. Applying Two-Photon Excitation Fluorescence Lifetime Imaging Microscopy to Study Photosynthesis in Plant Leaves. *Photosynthesis Research* **2009**, *100*, 89−96.

(72) Hohng, S.; Ha, T. Single-Molecule Quantum-Dot Fluorescence Resonance Energy Transfer. *ChemPhysChem* **2005**, *6*, 956−960.

(73) Faizan, M.; Karabulut, F.; Alam, P.; Yusuf, M.; Tonny, S. H.; Adil, M. F.; Sehar, S.; Ahmed, S. M.; Hayat, S. Nanobionics: A Sustainable Agricultural Approach towards Understanding Plant Response to Heavy Metals, Drought, and Salt Stress. *Nanomaterials* **2023**, *13*, 974.

(74) Wang, X.; Xie, H.; Wang, P.; Yin, H. Nanoparticles in Plants: Uptake, Transport and Physiological Activity in Leaf and Root. *Materials* **2023**, *16*, 3097−3097.

(75) Wei, L.; Liu, J.; Jiang, G. Nanoparticle-Specific Transformations Dictate Nanoparticle Effects Associated with Plants and Implications for Nanotechnology Use in Agriculture. *Nature Comm.* **2024**, *15*, 7389.

(76) Gui, X.; Zhang, Z.; Liu, S.; Ma, Y.; Zhang, P.; He, X.; Li, Y.; Zhang, J.; Li, H.; Rui, Y.; Liu, L.; Cao, W. Fate and Phytotoxicity of CeO_2 Nanoparticles on Lettuce Cultured in the Potting Soil Environment. *PLoS One* **2015**, *10*, No. e0134261.

(77) Guzmán-Báez, G. A.; Trejo-Téllez, L. I.; Ramírez-Olvera, S. M.; Salinas-Ruíz, J.; Bello-Bello, J. J.; Alcántar-González, G.; Hidalgo-Contreras, J. V.; Gómez-Merino, F. C. Silver Nanoparticles Increase Nitrogen, Phosphorus, and Potassium Concentrations in Leaves and Stimulate Root Length and Number of Roots in Tomato Seedlings in a Hormetic Manner. *Dose-Response* **2021**, *19*, 155932582110445.

(78) Hu, J.; Jia, W.; Wu, X.; Zhang, H.; Wang, Y.; Liu, J.; Yang, Y.; Tao, S.; Wang, X. Carbon Dots Can Strongly Promote Photosynthesis in Lettuce (Lactuca Sativa L.). *Environ. Sci. Nano* **2022**, *9* (4), 1530−1540.

(79) Wu, H.; Peng, T.; Li, X.; Zhao, Y.; Huang, F.; Guo, P.; Lyu, M.; Yin, J.; Liu, Q.; Gouda, S.; Mohamed, I.; Huang, Q.; Wang, X. Effects of Aging Biodegradable Agricultural Films on Soil Physicochemical Properties and Heavy Metal Speciation. *Toxics* **2025**, *13*, 245.