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Photoluminescent Polymer Nanocomposites: Innovative Materials for Enhanced Light Management and Crop Yield Optimization

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Abstract. Light is essential for plant growth and plays a crucial role in photosynthesis. However, sunlight often falls short of ensuring photosynthesis efficiency due to its wavelength composition, changing weather conditions, and the unique characteristics of plants, which create challenges for agricultural productivity. To address this, many innovative farming practices have been developed, including controlled environment agriculture, which creates microclimates that optimize conditions for plants. To improve light efficiency in these microclimates, researchers have turned to luminescent and light-conversion materials. These materials are incorporated into polymers to convert underutilized wavelengths, such as ultraviolet-visible (UV) and blue light, into photosynthetically active radiation (PAR). Luminescent materials like fluorescent pigments, quantum dots, and rare-earth-doped compounds, when incorporated into polymers, produce films that enhance light absorption and improve spectral energy distribution. They have shown great potential to increase crop yield, biomass, and the quality of fruits and vegetables. Despite their potential, challenges remain on the path to widespread adoption. Environmental impact, scalability, and economic feasibility are significant concerns. This review explores the integration and functionality of photoluminescent polymer nanocomposites as light-converting materials. It also examines current limitations while offering future perspectives on how these materials can be used for sustainable light solutions to improve agricultural productivity.

Introduction

Agriculture thrives on light and light is a fundamental element driving photosynthesis—the process that transforms sunlight into the energy plants need to grow. While light is essential for plant health, its availability is often inconsistent [1-4]. Some regions face challenges of insufficient sunlight, while others contend with excessive exposure, leading to plant stress and reduced yields. Climate change further aggravates these challenges, exacerbating external stressors and stagnating crop productivity. With the global population increasing and per capita arable land decreasing, these challenges demand urgent solutions [5-8].
Controlled Environment Agriculture (CEA) provides a promising path forward and involves using precisely regulated conditions to enhance crop efficiency and resilience. In CEA, regulated light

exposure ensures optimal growing conditions. However, using artificial lighting systems can significantly increase the operational costs of farms [3, 5, 7, 9-11]. A promising alternative is photoluminescent polymer composites. These materials absorb natural or artificial light and re-emit it as wavelengths optimized for photosynthesis, enhancing plant growth, reducing energy waste, and potentially increasing crop yields. This article reviews the potential of photoluminescent polymers in agriculture, focusing on their role in addressing light-related challenges and enhancing photosynthetic efficiency. It highlights their contributions to sustainable farming practices through innovative light management techniques. It also explores the synthesis of these polymers, reported increases in productivity due to their integration into farming systems, and future perspectives for improved outcomes.

Factors that affect photosynthesis

Photosynthesis is a biochemical process in which plants and certain microorganisms convert gaseous carbon (iv) oxide and water into glucose in the presence of light. The glucose formed is stored or used for their growth and development. This process also replenishes oxygen in the atmosphere. This process occurs in chloroplasts through light absorption by chlorophyll which triggers electron transport and a series of enzymatic reactions that produce essential organic compounds and release oxygen. It is dependent on internal factors, such as chlorophyll content, stomatal function, leaf structure, and nutrient availability. Nutrients like nitrogen and magnesium support chlorophyll production and enzymatic activity and are therefore vital contributors. Also, younger, healthier plants photosynthesize more efficiently than older or stressed ones [12-15]. External factors play an equally crucial role: Photosynthetic rate is influenced by light quality, particularly red and blue wavelengths. Atmospheric carbon (iv) oxide levels and temperature also impact enzyme activity. Stressors like pollution and extreme weather damage plant tissues, reducing photosynthetic efficiency and highlighting the need for balance [12, 15, 16].

Light and its crucial role in photosynthesis

The Sun provides warmth to sustain life and sunlight for visibility and photosynthesis [1]. Using sunlight, plants convert carbon (iv) oxide from the air and water absorbed from the soil into glucose ($C_6H_{12}O_6$) and oxygen (O_2) [17, 18] through the summarized chemical reaction below (Equation 1):

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \text{Equation 1}$$

Sunlight comprises 55 % infrared, 43 % visible light, and 2 % ultraviolet radiation, each uniquely contributing to plant growth [19, 20]. Chlorophyll absorbs light most effectively in the blue (430 – 450 nm) and red (640 – 680 nm) regions of the spectrum. Beyond these wavelengths, photosynthetic efficiency declines particularly for above 680 nm. However, the Emerson enhancement effect demonstrates that combining long- and short-wavelength photons boosts photosynthetic activity. So, far-red photons aid photosynthesis in shaded environments, while green photons penetrate deeper into plant tissues, enhancing carbon fixation [9, 21-24].

In terms of the availability of optimal light wavelength, useable light for plant activities is limited by various factors. For example, seasonal changes affect light availability and can also affect crop growth cycles. In spring and summer longer daylight hours provide more sunlight for photosynthesis which leads to vigorous growth and higher yields while shorter days in autumn and winter result in reduced light availability and slower growth rates, especially in crops that are sensitive to light. While some amount of shade can favor some types of plants, excessive shading can be deleterious. Campos et al. and Costa et al. demonstrated the effects of shading on plant growth by comparing greenhouses with and without reflective aluminized shading materials. The results demonstrated that appropriate shading can enhance yield quality by decreasing unmarketable fruit [25, 26]. However, structures in urban environments can create artificial covers and shadows beyond the control of farmers, thereby limiting sunlight reception for crops. The erratic nature of weather due to climate change worsens these issues through cloud cover and frequent storms which may cause inconsistent sunlight exposure during critical growth periods. Insufficient light conditions harm the physical structure, health, and weak immunity of plants against pests and diseases [6, 27]. Conversely, excessive light can cause photoinhibition where plants are overwhelmed and cannot process it effectively. This condition causes photo stress and reduces photosynthetic performance and reactive oxygen species (ROS) accumulation in plant cells which then damages chlorophyll molecules and disrupts photosynthetic pathways. Excess UV exposure damages plant DNA, negatively affecting growth [3, 28-31].

Claypool et al. confirmed that broad-spectrum light is most effective for plant growth, in line with the Emerson effect. Their study on bell pepper seedlings revealed that green light significantly improved physical characteristics such as plant height and leaf area compared to monochromatic red or blue light [32]. Also, in an attempt to supplement natural sunlight with artificial light enhancement, Adibian et al. used various combinations of red and blue light-emitting diodes (LEDs) and observed an enhancement in fruit yield and quality parameters of sweet pepper (*Capsicum annuum L.*) grown in greenhouses under low natural sunlight conditions [33]. Similarly, Hyeon-Do et al. observed that artificial Red-Green-Blue (RGB) LED lighting resulted in the highest chlorophyll content and overall seedling vigor in the germination of lettuce cultivars compared to each light alone [27].

These observations are helpful for modern farmers who can adopt farming practices independent of sunlight in the form of Controlled Environment Agriculture (CEA), although energy consumption challenges the feasibility of this method. While the decreasing cost of LEDs and improvements in efficiency and smart systems designed for adjusting light spectra can help reduce operational costs, innovative light management systems such as spectra-shaping films and sunlight redirection methods are also emerging [7, 12, 34]. Sunlight remains the most cost-effective light source and there are ongoing efforts to optimize its use while minimizing damage from harmful wavelengths. One of these methods involves the use of polymers and their nanocomposites.

Polymers

Polymers are macromolecules formed from repeating units called monomers. Natural examples include proteins in animals and cellulose in plants, while synthetic polymers such as plastics and rubbers are chemically engineered. Nowadays their application cuts across many spaces since they are cheap substitutes for metals and ceramic materials [35-37]. The modern understanding of polymers began in the 19th century with discoveries like the vulcanization of rubber by Charles Goodyear and the synthesis of the first synthetic plastic, Bakelite, by Leo Baekeland during the same period. Since then, many more synthetic polymers such as polyethylene, polystyrene, and nylon have been made and used in household and technological products [38].

Polymers can be classified based on their origin, structure, and properties. Natural polymers have complex structures that play critical roles in biological processes. In contrast, synthetic polymers may be engineered for specific applications. Structurally, polymers could be linear polymers (e.g., polyvinyl chloride), branched polymers (e.g., low-density polyethylene), and cross-linked polymers (e.g., Bakelite). Polymers are synthesized through methods categorized as either addition or condensation polymerization. In addition polymerization, monomers have a double or triple bond and are therefore joined through a bond-opening reaction that does not result in the loss of small molecules, while condensation polymerization involves reactions that release by-products like water or methanol. Examples of polymers formed through addition polymerization include polyethylene and polypropylene while polymers like nylon and polyester are formed through condensation reaction [39-41].

Applications of polymers in agriculture

Polymers play an essential role in modern agriculture by enhancing productivity and efficiency. Their versatile properties make them invaluable for various applications, particularly in farming systems such as greenhouses, mulching, and irrigation. These materials provide benefits such as improved soil temperature control, moisture retention, and protection of crops from external stressors like pests and extreme weather. Their global adoption in farming practices is inked with their cost-effectiveness and ease of adoption [42-45].

Polymers such as polyethylene, polyvinyl chloride (PVC), and polypropylene are commonly used due to their favorable physical and chemical properties. Polyethylene, particularly low-density polyethylene (LDPE) is a widely used polymer in agriculture. It is used in the production of greenhouse covers and mulch films. It is strong enough to provide a barrier against pests and weeds while being optimally transparent for adequate sunlight penetration. It is flexible and can conform to soil surfaces. Its impermeability helps retain moisture and regulate soil temperature which is very beneficial in arid regions where water conservation is paramount. Innovative applications of polyethylene have led to the production of films with varying thicknesses and colors to modify light absorption and reflectance properties for specific crops. For example, clear polyethylene film maximizes light transmission and is ideal for regions with abundant sunlight. White diffused polyethylene film produces a gentler lightening effect and warmth by scattering sunlight which prevents scorching of delicate plants. Black-and-white films produce controlled light exposure also referred to as photoperiod control. The effects of light-diffusing and clear film on the growth of Batavia lettuce (*Lactuca sativa L.*) in two greenhouses over five growth periods were studied by [46]. Results indicated that lettuce grown under the light-diffusing film was smaller (up to 36 %) and had fewer leaves with reduced leaf area. However, they had higher total macroelement contents (up to 10 %) and increased leaf nitrate levels than their counterpart cultivated under the clear film. This supports the need for specificity in the application of light diffusion films [46]. Also, the effects of polyolefin (PO) film and ethylene-vinyl acetate (EVA) film on lettuce growth were compared. It was observed that greenhouses covered with PO had higher temperatures and humidity. In addition, PO film provided more average illumination intensity of 293.22 μmol m^2 s^{-1} and 80.37 % light transmittance, compared to 193.04 μmol m^2 s^{-1} and 52.91 % for EVA film. The PO film also enhanced chlorophyll content and crop productivity which indicates potential for effective use in vegetable cultivation [47]. Polypropylene is also used as covers, spreads, and plant pots because it has high tensile strength and is resistant to chemical degradation, making it suitable for harsh chemical environments. Polypropylene fabrics are often used to suppress weed growth in the form of landscape fabrics which allow water and nutrients to permeate the soil [48, 49].

Limitations of traditional polymers light optimization

Conventional polymers are limited in light applications in agricultural settings. For example, noncolored traditional agricultural films primarily provide a barrier against environmental factors rather than optimizing light quality. Even the colored ones do not adequately filter harmful ultraviolet (UV) radiation or adjust the light spectrum to favor specific wavelengths that enhance plant growth. Also, most polymers become brittle after prolonged exposure to UV radiation due to photo-oxidative degradation of their polymer chains. This causes a loss of mechanical properties, reduced functionality, and reduced lifespan. As they degrade, they may become less effective at regulating temperature or moisture levels around crops which translates to increased costs for farmers due to replacements [50-52].

Photoluminescent materials

Photoluminescent materials (PMs) have emerged as pivotal components in various fields, including optoelectronics, lighting, display technologies, personalized medicine, and agriculture due to their high energy efficiency and stability [53, 54]. Photoluminescence refers to the emission of light by a material after it absorbs photons, which excites electrons to higher energy levels. These electrons release energy as they return to their ground state, making the materials with such ability invaluable for light conversion and enhancement applications. However, photoluminescence can be an upconversion or downconversion process where light is either absorbed or emitted at different energy levels. Upconversion occurs when lower-energy photons are absorbed and re-emitted as higher-energy photons, like in a material that converts infrared light into visible light, as seen in upconverting phosphors [55-57]. In contrast, downconversion involves the absorption of high-energy photons, which are then re-emitted as lower-energy photons, such as when ultraviolet light is absorbed and emitted as visible light in phosphorescent materials [58-60]. In practical terms, down-converting luminous material, $SrAl_2O_4:Eu^{2+}$, Dy^{3+}, was developed by Zhu et al. to emit red light in the dark after excitation by combining a light conversion agent with $SrAl_2O_4:Eu^{2+}$, Dy^{3+} [61]. Also, $Sr_{0.46}Ba_{0.50}Yb_{0.02}Er_{0.02}F_{2.04}$ nanoparticles synthesized by [57] were used as up-converting luminophores, capable of converting infrared radiation into visible light, with emissions observed at 660 nm, 545 nm, and 525 nm for possible photosynthesis applications [57].

Broadly, PMs can be classified into fluorescent dyes, conjugated polymers, organic rare-earth complexes, and inorganic rare-earth complexes. Each category offers specific advantages in luminescent polymer application. Fluorescent dyes, such as 2-([1,1′-biphenyl]-4-yl)-3,3-diphenylacrylonitrile [62], 2,4,6-tris (4-methoxy-3-methyl-N-phenylaniline) 1,3,5-triazine [1], and 3- and 4-position naphthalimide [63] have been embedded in polymers. Organic rare earth complexes have metal ion luminescent centers surrounded by organic ligands. Qiao et al. developed luminescent kaolinite clay by incorporating N-methylimidazole (NMI) molecules and Eu^{3+}/Tb^{3+} salts into it. The luminescent material was thereafter incorporated into polyvinylidene fluoride [64]. Inorganic rare-earth complexes on the other hand are purely inorganic. Examples are Eu-doped $Sr_2Si_5N_8$ which was embedded into low-density polyethylene [65] and Eu-doped calcium carbonate was incorporated into polyethylene [66]. Similarly, another sunlight-converting film made from $BaMgGa_3Al_7O_{17}$:$0.2Cr^{3+}$ supported the growth of Chlorella as a broadband near-infrared converter [67].

An ideal photoconversion system for photosynthetic applications should possess several features: efficient solar spectrum transmittance in photosynthetically active ranges, sufficiently high quantum yield of re-emission, suitable surface modifications for targeted photoreactions, high chemical, and photostability, and minimized reabsorption losses [68]. Such PMs absorb sunlight, typically in the UV or green spectrum (460 – 560 nm), and re-emit it as red light (~ 660 nm). By this, they play an active part in enhancing photosynthetically active radiation. This re-emission aligns with the absorption spectrum of chlorophyll-a, a critical pigment in photosystem II, thus improving photosynthetic efficiency even in low-light or diffuse-light environments.

Polymer nanocomposites (PNCs) and photoluminescent polymer nanocomposites (PPNCs)

Generally, polymer nanocomposites (PNCs) consist of a polymer matrix with nanoparticles dispersed within it [69]. Usually, nanofillers, which can have various morphological characteristics, modify the polymer matrix's mechanical strength, thermal stability, barrier performance, electrical conductivity, and optical properties. The large surface area and high aspect ratio of the nanofillers facilitate strong interactions with the polymer material. Nanomaterials like silica, calcium carbonate, graphene, or metal oxides have been used to improve the functionality of polymers [69-71]. Many non-luminescent polymer composites have been made using non-luminescent materials. Such films have also been used in agricultural settings. For example, a study investigated the effects of different colored light-quality selective plastic films (transparent, red, yellow, green, blue, and purple) on the growth, photosynthetic abilities, and fruit quality of strawberries. The results indicated that the red film significantly enhanced leaf area, petiole length, and biomass, improved photosynthetic performance by increasing pigment content and quantum yield while reducing energy dissipation as heat, and also boosted fruit weight along with the content of total sugar, anthocyanin, and soluble protein, suggesting that red light is optimal for strawberry production [72].

However, Photoluminescent Polymer nanocomposites (PPNCs) are unique in the fact that the nanofillers used have photoluminescent properties. In agricultural settings, PPNCs are used as light conversion films in greenhouse and field planting areas to improve sunlight utilization as shown in Fig. 1. Depending on the purpose and the type of photoluminescent materials embedded in the polymer matrix, PPNCs can exhibit various optical properties. When carbon-based nanomaterials, which have photoluminescent properties, are incorporated into films, they produce effective down-conversion PPNCs for converting ultraviolet (UV) light into radiation that plants can use for photosynthesis [73-75]. For example, vinyl alcohol-encapsulated carbon dots (CDs) have demonstrated the ability to convert UV light into blue light, which significantly improves photosynthetic efficiency in lettuce [76]. Similarly, amine-functionalized CDs can bind effectively to chloroplast surfaces, enhancing photosynthesis by facilitating a faster solar energy conversion [77]. In a study by Li et al., researchers created an innovative dual-wavelength luminescent CD that not only absorbs UV light efficiently but also emits blue and red light, perfectly matching the wavelengths that chloroplasts can absorb [78]. He et al. developed a light conversion film by embedding blue-light-emitting carbon dots (CDs) with red-light-emitting europium ions (Eu^{3+}) in a polyvinyl alcohol (PVA) matrix through the direct recombination method. The research demonstrated that the photoluminescence properties of the composite could be tuned by adjusting the ratio of CDs to doped Eu^{3+}, allowing for customized light components to meet the specific needs of different plant species [79]. Barman et al. reported the synthesis of a transparent plastic material that effectively blocks ultraviolet (UV) light while emitting blue light at 440 nm, using polyvinyl alcohol (PVA) as the matrix to disperse nitrogen-doped carbon dots (N-CDs) created through a hydrothermal process. The resulting N-CD/PVA composite achieves a quantum yield of 91 % when excited in the UV-A range (350–370 nm), demonstrating enhanced UV absorption proportional to film thickness without compromising luminescence, making it a promising eco-friendly solution for applications such as UV shielding, anti-counterfeiting, and greenhouse sheathing to promote plant growth [80]. Also, the rare-earth material $CaAlSiN_3:Eu^{2+}$ and its (3-Aminopropyl) triethoxysilane (KH550)-modified version enhanced the crystallinity of polylactide (PLA) films and improved red-light conversion. These films emitted fluorescence at UV wavelengths of 254 nm and 365 nm, significantly promoting plant growth [81]. Wu et al. observed the average diameter of light conversion filler in the $Sr_2Si_5N_8:Eu^{2+}$-based film to be 500 nm, and for the film's mechanical properties, it was observed that the tensile strength of the film increased from 9.86 to 12.16 MPa and the strain at breakage rose from 2.37 % to 2.75 % when compared with the blank film. The film also effectively converted UV to plant-friendly red light [65].

Films containing luminescent $CuInS_2$/ZnS quantum dots (QD) were also used to modify the solar spectrum to improve plant productivity and in bioregenerative life-support systems for potential human settlements beyond Earth. The results showed that these QD films effectively down-converted ultraviolet and blue light to red emissions at 600 and 660 nm, leading to significant increases in biomass accumulation in red romaine lettuce, with edible dry mass increasing by 13 % and 9 %, respectively, and total leaf area increasing by up to 13 %, indicating enhanced photosynthetic efficiency and potential for greater productivity in both terrestrial greenhouses and space environments [82].

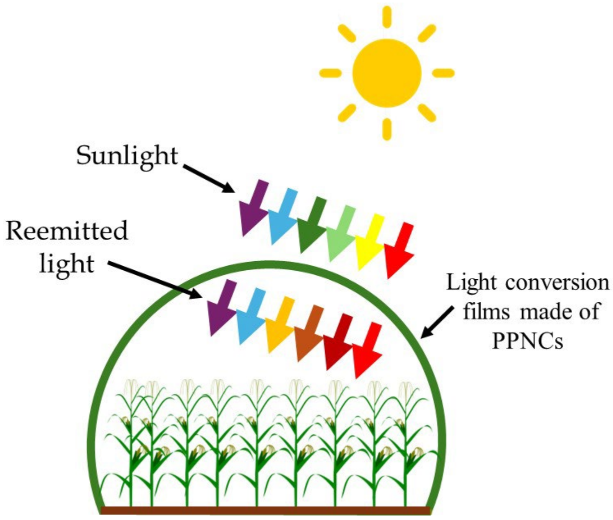

Fig. 1. Light conversion attributes of photoluminescent polymer nanocomposites.

Fabrication of PPNCs

The method used to fabricate PPNCs can influence their performance due to the degree of dispersion and interaction of nanofillers within the polymer matrix. Common methods like in situ polymerization, solution mixing, and melt blending are applicable depending on the desired properties of the final composite, and each method offers specific advantages tailored to those properties as shown in Fig. 2. Table 1 compares the various methods discussed below.

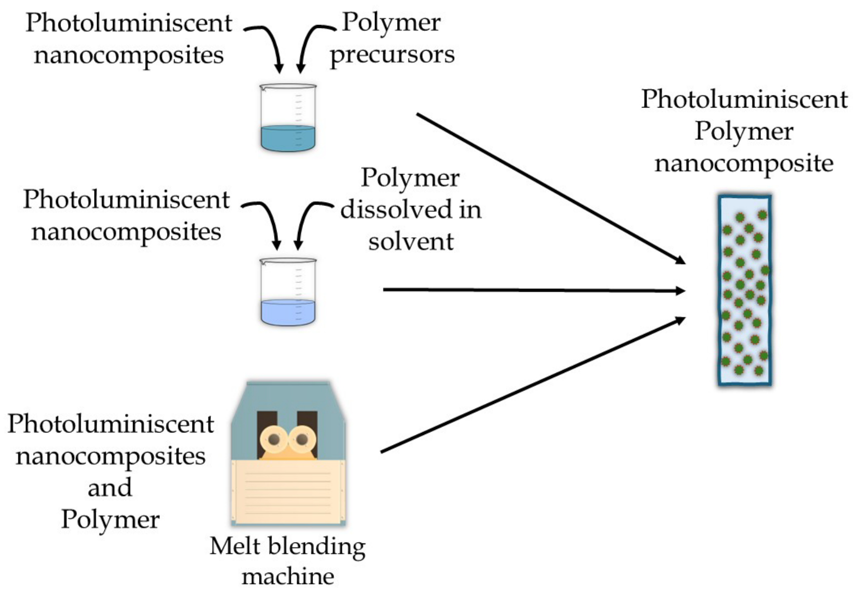

Fig. 2. Methods of photoluminescent polymer synthesis

In situ polymerization involves the polymerization of monomers in the presence of dispersed photoluminescent nanoparticles and offers the advantage of strong interfacial bonding and uniform integration. The light-emitting nanoparticle materials are mixed with polymer monomers before polymerization to create solid-state polymer nanocomposites. Zhang et al. reported a semi-aromatic polyamides polymer composite made with upconversion nanoparticles in a one-pot double in-situ synthetic method combining hydrothermal and melt polycondensation techniques [83]. De et al. also synthesized hyperbranched epoxy resin/carbon dots polymer nanocomposite with in situ incorporation of carbon dots during the formation of hyperbranched epoxy resin [84]. Both authors reported transparent uniformly dispersed and photoluminescent materials. Shi et al. synthesized $CsPbBr_3$ nanocrystals in methyl methacrylate via a one-pot method. They achieved a high quantum yield of 85 % and narrow emission linewidth of 20 nm. The UV-cured PNC–PMMA films were stable and showed improved optical performance [85]. Jang et al. took a different approach by dispersing QDs in a siloxane resin to create a thermally stable QD/siloxane hybrid, which proved to be highly stable even under extreme conditions [86].
Solution mixing is effective when there is a solvent that can interact effectively with both the fillers and polymer matrix. The solution is evaporated after the composition is formed. It is effective for both thermosetting and thermoplastic polymers provided the right solvent is used. This method allows the use of techniques like molding, spin-coating, dip-coating, electrospinning, and drop-casting, to refine the final structure of the composites. For example, carbon dot (CD)/polymer composites in the form of supraballs, films, and fibers have been fabricated using solution-based methods [87-90]. Polymers commonly used for these processes include polyvinyl alcohol (PVA), chitosan, polycaprolactone (PCL), and polyvinyl pyrrolidone (PVP) [91-93]. Mutlugun et al. used this approach to embed QDs into PMMA films using hexane as a solvent which produced materials with quantum yields exceeding 90 % and vibrant color output [94]. Similarly, Chen et al. fabricated QD/acrylate films by incorporating green and red QDs into a UV-curable acrylic resin. The approximately 320 µm thick films were made by coating the mixture onto PET substrates and curing under a mercury lamp [95].
Melt blending, or melt mixing, involves dispersing the nanoparticles into a molten polymer using extruders and kneaders. It is better suited for thermoplastic polymers like polyethylene or polypropylene and offers scalability. It is also cheap to implement and solvent-free [65, 96, 97]. Strontium aluminate phosphors ($SrAl_2O_4$:Eu,Dy and $Sr_4Al_{14}O_{25}$:Eu,Dy) were combined with low-density polyethylene, high-density polyethylene, polypropylene matrices by melt mixing and extrusion and the luminescence and durability were observed using the Hamburg wheel test. It was observed that the polymer matrix affected the luminescence of the composite although their emission wavelength was retained [97].

Table 1. Comparison between different methods of photoluminescent polymer synthesis.

Method	Polymerization	Solvent Usage	High Shear Forces	Thermal Processing	Key Advantage	Limitations	References
In Situ Polymerization	Yes	Optional	No	No	Strong nanoparticle-polymer bonding.	Complex processing conditions required.	[83, 84]
Solution Mixing	No	Yes	No	No	Excellent dispersion of nanoparticles.	Potential solvent residue issues.	[89, 94]
Melt Blending	No	No	Yes	Yes	Solvent-free and scalable process.	Limited to thermoplastic materials.	[96, 97]

Factors influencing the performance and stability of PPNCs

The design of PPNCs involves several critical factors: the choice of luminescent materials, the polymer matrix, the fabrication method, and the dispersion of nanomaterials within the matrix. The polymer matrix must not exhibit quenching effects on the luminescent materials and should efficiently scatter light to ensure uniform distribution of re-emitted light. The dispersion of nanoparticles within the polymer matrix is crucial. Fillers with strong Van der Waals forces tend to aggregate, reducing the effective surface area available for polymer-nanocomposite interaction. Aggregation also creates weak points in the composite thereby weakening the mechanical, thermal, and electrical properties of the product. It has been observed that surface modification or functionalization of nanoparticles enhances their compatibility when integrated into polymer matrices.

Surface modification may introduce functional groups or protective shells around nanoparticles which improve their bonding with polymers and enhance dispersion, stability, and thermal resistance as shown in Fig. 3. Surface modification of nanoparticles may also increase their surface area or increase active sites which aid blending into both synthetic and natural polymer matrices. Treating nanoparticles with silanes, surfactants, or grafted polymers enhances compatibility with the polymer matrix and improves dispersion [98-102]. In the case of photoluminescent materials surface modification improves stability and minimizes photoluminescence quenching which results from aggregation [103-105]. Surface modification of quantum dots was carried out using mercaptopropionic polyethyleneimine (MPPEI) to create acid and base-resistant photoluminescent particles whose quantum yield of above 86 % [106]. Wang et al. achieved surface modification of ZnS-based QDs using 3-Mercaptopropyltrimethoxysilane ligands for effective dispersion into bacterial cellulose and reported a quantum yield of about 35 % [107]. Surface modification of photoluminescent salicylic acid and o-phenanthroline doped Eu^{3+}, Sm^{3+}, and Y^{3+} was carried out thereafter light conversion films were produced by incorporating them into ethylene-1-hexene copolymer film through blow molding. The film effectively converted ultraviolet light (250 – 400 nm) to red light (610 – 660 nm) which indicates suitability for plant photosynthesis and performance for agricultural applications [108]. In addition, highly resistant and vapor-proof films based on fluoropolymers, combined with nanoparticles or quantum dots, have demonstrated the ability to convert UV and violet light into blue and red wavelengths, enhancing photosynthesis and plant growth without additional energy consumption. These coatings maintain stability under fluctuating weather conditions, which is vital for agricultural resilience [57, 109].

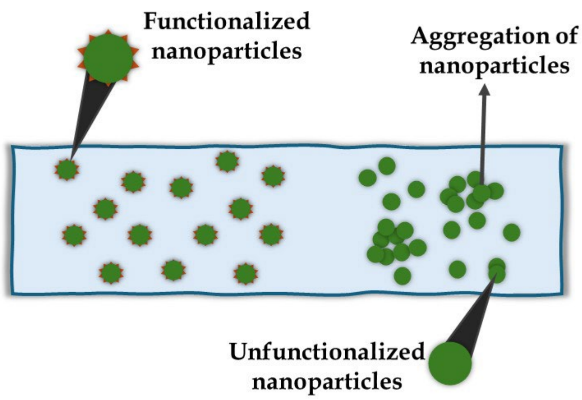

Fig. 3. Effect of surface modification on photoluminescent nanoparticles in polymer matrices.

Assessing the effectiveness of surface modification and the dispersion of fillers in polymer composites is a necessary aspect of the characterization process. This evaluation often requires a combination of analytical techniques, including Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Energy-Dispersive X-ray Spectroscopy (EDX). SEM generates high-resolution images of the polymer surface which shows the distribution of filler particles and any agglomeration or uneven dispersion present. TEM offers a nanoscale perspective for confirming homogeneity and detection of any phase separation through visualization of the fillers' integration within the polymer matrix at the molecular level. When coupled with SEM, EDX maps the elemental composition, offering precise insights into the spatial distribution of fillers and ensuring their uniform integration across the polymer. Together, these techniques deliver a comprehensive analysis of filler dispersion, verifying their effective incorporation into the polymer matrix and contributing to the overall performance and reliability of the PPNC [110-115].

Impact of photoluminescent films on crop farming

Using the physical attributes of plants and quality parameters of crops the benefits of PPNCs have been established as highlighted in Table 2. This enhances growth conditions by mimicking natural sunlight, with red light boosting fruiting and flowering and blue light supporting leafy growth, addressing natural light inefficiencies that limit crop yields. Enhanced light availability also bolsters plant immunity, resulting in stronger, more resilient crops [116-118]. Research in China has focused on developing these films since the late 1980s, leading to innovations such as the incorporation of rare earth elements and various light conversion agents into polyethylene and polyvinyl chloride films, which have demonstrated increases in crop yields and improved quality. Notable developments include the introduction of light conversion films that enhance the growth of crops like rice, tomatoes, and cucumbers by optimizing light conditions in greenhouses. Ongoing research aims to further improve the efficiency and functionality of these films, with projections indicating significant growth in the agricultural film industry by 2026 [119].

Studies demonstrate the transformative effects of integrating photoluminescent materials into greenhouse films. Modified light spectra, such as green-to-red (GtR) conversions, have significantly boosted crop yields, plant biomass, and fruit quality. For instance, sweet pepper plants exposed to GtR films exhibited enhanced photosynthesis, with 12 – 18 % higher chlorophyll fluorescence, improved photosynthetic light-response curves, and greater dry mass accumulation. These findings highlighted the role of optimized light conditions in elevating photosynthetic efficiency. Not only that, it was observed that the GtR-modified spectrum enhanced dry mass, improved photosynthetic light-response curves, and significantly increased chlorophyll fluorescence parameters, indicating better electron transfer and overall photosynthetic efficiency [120].

Specific applications of these films have demonstrated remarkable results. For example, $Sr_2Si_5N_8:Eu^{2+}$-based films improved the growth and nutritional profile of Chinese flowering cabbages, increasing plant dimensions by up to 24 % and enhancing polyphenol, protein, and sugar content [65]. Similarly, Gao et al. reported that rare-earth light conversion films (RPO) enhanced the growth and yield of sweet peppers by improving the temperature and light conditions. They also recorded better fruit quality and high nutritive value in terms of ascorbic acid (Vitamin C), soluble protein, and soluble sugar. These films increased photosynthetic activity and plant hormone levels (gibberellic acid 3, indole-3-acetic acid (IAA), and zeatin riboside), resulting in a 20.34 % yield improvement compared to polyolefin films [121].

Another study by Yanykin et al. demonstrated the effects of glasses coated with up-converting luminescent nanoparticles on tomato cultivation. Using $Sr_{0.46}Ba_{0.50}Yb_{0.02}Er_{0.02}F_{2.04}$ nanoparticles, tomatoes exhibited a 33 % increase in total leaf area, a 35 % increase in stem length, improved chlorophyll content, and reduced recovery time for photosystem II quantum yield from three weeks to three days. These results affirm that increased red light in the growth spectrum enhances photosynthetic activity and overall plant development [57].

Beyond optimizing light conditions, these films also provide thermal regulation by converting UV light, which can accelerate surface water loss, into photosynthetically active radiation (PAR), thereby reducing heat stress and maintaining ideal growing conditions. This feature is particularly valuable in extreme climates such as those in the Middle East and Sub-Saharan Africa [42, 122-124]. Additionally, incorporating photoluminescent materials into greenhouse systems facilitates energy-saving solutions, such as solar-powered lighting and irrigation. These innovations reduce reliance on artificial lighting and lower energy costs, making them essential for sustainable agriculture and future food security. PPNCs polymers can improve soil quality by fostering beneficial microbial activity and enhancing nutrient availability through their capacity to retain moisture and decrease reliance on chemical fertilizers creating a balanced soil environment that supports healthy plant growth [1, 125].

Table 2. Impact of Luminescent and Light-Conversion Materials on Crop Growth, Yield, and Quality

Crop	Luminescent Material	Polymer/Film	PAR/Light Effects	Growth Effects	Quality Effects	Additional Benefits	Refe-rence
Strawberry (*Fragaria x ananassa* 'Elsanta')	Fluorescent pigments (Blue, Red1, Red2, Red3)	Photoselective greenhouse films	Blue pigments increased total PAR transmission (1 – 3 %), while Red pigments lowered it. Red3 increased red: far-red ratio by 10 %.	Blue films increased fruit production by 11 %; Red3 films delayed production and reduced yield by 10 %.	Blue films produced brighter, more saturated fruits but with higher acidity (lower pH). Red films produced sweeter fruits due to lower acidity.	Blue films showed potential for enhancing fruit yield and quality, while red films negatively impacted yield.	[126]
Red romaine lettuce (*Lactuca sativa*)	CuInS2/ZnS quantum dots	Luminescent QD films	Converted UV/blue to red (600 and 660 nm)	Increased dry mass (13 %, 9 %) and fresh mass (11 %); larger leaf area (8 %, 13 %).	Photosynthetic efficiency 13 %	Boosts plant productivity in greenhouses on Earth and space environments. Provided	[82]
Cabbage (*Brassica oleracea var. capitata*) and lettuce (*Lactuca sativa*)	Yttrium oxysulfide doped with europium photoluminophore	Photoluminescent spunbond fabric	Converted UV to red light (610 – 640 nm); improved RL/FRL ratio.	Increased biomass by 30 – 50 %; improved water-use efficiency; reduced transpiration and stomatal conductance.	Enhanced photosynthesis, phytochrome activation, and stress resistance.	Boosts growth via spectral optimization and soil microflora interaction; increases productivity in shaded areas.	[127]
Chinese flowering cabbage (*Brassica rapa*)	Light-conversion agents (500 nm average diameter)	Low-density polyethylene	Enhanced red-orange light (600 - 700 nm), reduced blue (under 560 nm) and UV light	Increased plant height (24.43 %), leaf length (15.30 %), leaf width (15.60 %), leaf breadth (19.07 %)	increased soluble protein (9.09 %), polyphenol content (21.27 %), soluble sugar content (19.15 %)	improved biomass, increased chlorophyll and carotenoid content, and enhanced photosynthesis leading to better	[65]

						fresh and dry weights of plants	
Sweet pepper (*Capsicum annuum L.*)	Rare-earth (Eu	Polyolefin films	Higher blue, red-orange, and far-red light transmission, lower UV, violet, and green light transmission.	11.05 % increase in plant height, 16.96 % increase in stem diameter, 25.27 % increase in internode length.	Increased fruit length, width, average fruit weight, and yield by 20.34 %. Increased ascorbic acid by 14.29 %, soluble protein by 47.10 %, and soluble sugar by 67.69 %.	Increased photosynthesis, Rubisco activity, and improved fruit quality with higher yield. Higher temperature inside the greenhouse, improving growth conditions.	[128]
Tomato	Gold nanoparticles, quantum dots (ZnSe, CdS)	Fluoropolymer film	Photoconverted UV and violet light into blue and red light, and partially converted green light into heat.	Increased leaf area by 50 % in 30 days, enhanced growth rate, higher photosynthetic intensity, higher chlorophyll content.	Higher CO_2 assimilation rate, increased production of ATP and NADH, improved synthetic processes and biomass production.	Reduced UV radiation exposure, suppression of stress signals, increased film durability, and enhanced productivity	[129]

Possibilities and challenges in sustainable use of photoluminescent nanocomposites

The high electricity demand for running greenhouses remains a significant drawback and challenges their sustainable operation [130, 131]. Integrating polymers and photoluminescent polymer nanocomposites (PPNCs) into agriculture presents exciting possibilities for advancing sustainable farming practices because it is dependent on the use of renewable energy which decreases the cost of energy and the footprint of controlled environment farming [3]. However, this integration is not without its challenges.

The practical implementation of these photoluminescent systems is hindered by several issues. Organic fluorophores are prone to rapid burnout, while rare-earth metal-based alternatives like europium, despite their improved stability, exhibit low quantum yield [68, 126, 132]. Furthermore, integrating nanoparticles with plasmon or exciton emissions, such as cadmium-selenium and zinc-sulfur, into polymer matrices remains challenging due to their sensitivity to reactive oxygen species generated during operation. This implies that there is a need for continued innovation in photoconversion technologies to balance performance with sustainability in agricultural practices [68, 133, 134] .

As the exploration of nanomaterial-based solutions increases concerns about biosafety and environmental impacts, especially for heavy-metal-based nanoparticles like cerium oxide and silver are rising and demand careful consideration. Issues such as nanoparticle aggregation, which reduces their effectiveness and raises toxicity risks, highlight the need for materials that are both stable and environmentally friendly. Advances in surface modifications, such as conjugation with chitosan, have shown promise; for instance, Cu–chitosan has enhanced plant growth while combating fungal pathogens. Similarly, alternatives like Mn_3O_4 nanoparticles, derived from essential micronutrients, offer safer options with their ability to scavenge reactive oxygen species (ROS) and boost plant stress resistance. Prioritizing non-toxic, nutrient-based nanomaterials with high dispersibility is essential for developing sustainable nano-enabled agricultural practices [135-137].

Integrating polymers and photoluminescent polymer nanocomposites (PPNCs) in agriculture offers a promising pathway toward sustainable farming practices. A key consideration in this integration is ensuring biodegradability, allowing these materials to break down over time and reducing the risk of microplastic accumulation in soils. This approach not only helps mitigate plastic pollution but also enhances long-term soil health [9]. Plastic contamination in agricultural soils is an escalating environmental concern due to its detrimental effects on the soil ecosystem and potential risks to water resources. Several studies have quantified and analyzed the distribution and sources of macro-plastics

(MaPs) and microplastics (MiPs) in agricultural soils under diverse farming systems. Greenhouse plastic contamination studies reveal significant MaPs and MiPs presence in surface and subsurface soils, as well as groundwater. Dominant contaminants include polyethylene and polyvinyl chloride, with microplastic concentrations averaging 225 ± 61.69 pieces/kg in greenhouse soils and 2.3 pieces/l in groundwater. Similarly, research in North China’s Quzhou County highlights variations in MaPs/MiPs across six farming systems, with cotton fields showing the highest contamination levels. The prevalence of MiPs in the 0–10 cm soil layer underscores the impact of tillage practices and plastic film usage, with polyethylene fragments (< 1 mm) being predominant. A strong correlation exists between plastic management practices and the size and abundance of soil plastics. A comprehensive review of 120 studies from 2018 to 2022 revealed Asia as the dominant region for research on agricultural soil plastic contamination (60 %) [43]. The studies emphasized mulching, sludge placement, and greenhouse abandonment as key contamination sources, and recommend density-based flotation methods like NaCl for light plastics and ZnCl for heavy plastics as efficient extraction techniques. These findings underline the necessity for sustainable plastic waste management in agriculture and further exploration of plastic fragmentation mechanisms and their effects on soil health [43-45, 138].

The cost implications of adopting these innovations present a challenge for farmers [1, 125]. Balancing profitability, performance, and environmental impact can be difficult, especially when considering the substantial initial investment required for implementing these light conversion technologies. Nevertheless, these costs can lead to significant long-term benefits. Improved light conditions can result in higher yields, enhancing profitability and providing a strong return on investment. Furthermore, the use of these polymers can increase crop resilience to pests and diseases, reducing the need for chemical pesticides and fertilizers. This not only lowers operational costs but also aligns with the growing consumer demand for sustainably produced food. A thorough economic analysis should take these factors into account, weighing initial expenses against potential savings from reduced input requirements and increased marketable yields.

Future directions for advanced photoluminescent polymers in agriculture

The use of photoluminescent polymer nanocomposites (PPNCs) in agriculture presents a promising frontier for sustainable farming practices. However, plastic contamination needs to be addressed creatively. Efforts to reduce plastic contamination are increasingly focusing on sustainable, renewable polymer nanocomposites. Biodegradable polymers like polylactic acid, polyhydroxyalkanoates, and polycaprolactone, when reinforced with nanoscale fillers such as cellulose nanocrystals, carbon nanostructures, and nanohydroxyapatite, offer promising solutions by maintaining strength, stability, and functionality while breaking down into environmentally safe byproducts [139-143]. Studies like those by Gouda et al. [144], Zhang et al. [145], and Singh et al. [146] highlight the potential of these composites, showing their capability in various applications, from smart windows and photoluminescent films to anti-counterfeiting technologies. Though not directly related to agricultural films, these innovations underscore the versatility of renewable polymers and their potential for reducing plastic contamination without sacrificing performance. However, current agricultural light conversion films, often based on rare earth elements like europium ions (Eu^{3+}), face significant challenges, including poor biodegradability and performance degradation under outdoor exposure [1, 147]. Future efforts should focus on developing eco-friendly alternatives that address these environmental concerns and optimize light conversion properties for agricultural applications, building on the insights gained from sustainable polymer nanocomposites.

PPNCs also hold the potential for precision farming through crop-specific designs. Looking to the future, the development of advanced photoluminescent polymers tailored to specific crop needs could revolutionize agricultural practices. By engineering materials to optimize specific spectral output, these polymers can significantly enhance photosynthetic efficiency, particularly for crops grown in shaded or suboptimal lighting conditions. This targeted approach will address yield challenges and mitigate the effects of environmental stressors. Additionally, these materials could contribute to soil conditioning by improving moisture retention and nutrient availability, creating a more favorable environment for plant root systems. Such advancements in soil amendment could further amplify the impact of PPNCs on agricultural productivity.

Nano-photoluminescent particles can be designed to dynamically adapt to fluctuating light conditions, ensuring optimal illumination throughout a crop's growth cycle. Pairing these materials with smart sensors capable of monitoring soil moisture, nutrient levels, and plant health could further refine resource allocation, reducing environmental impact and enhancing sustainability. Also, the adoption of these advanced materials requires a thorough evaluation of their environmental footprint. Comprehensive life cycle analyses will be crucial to assessing their sustainability from production through degradation. A critical research priority is improving their biodegradability by exploring biopolymer alternatives derived from renewable resources. Such efforts would ensure minimal disruption to soil ecosystems while enriching soil health through environmentally friendly degradation processes.

Pests and diseases remain persistent threats to global agriculture, and PPNCs could play a pivotal role in early detection and mitigation. Their fluorescence signaling capabilities can be adapted to monitor subtle changes in plant physiology, such as nutrient deficiencies or early-stage fungal infections, enabling timely interventions before visible symptoms arise. Furthermore, designing PPNCs that emit specific wavelengths to deter pests while optimizing light for photosynthesis could offer an eco-friendly alternative to chemical pesticides, fostering healthier ecosystems and reducing reliance on synthetic inputs.

The multifunctionality of PPNCs could extend beyond traditional applications, enabling their integration into IoT-enabled smart farming systems. Fluorescent probes embedded in PPNCs could facilitate real-time monitoring and site-specific management of crops through drones or autonomous systems. This technology would allow farmers to make precise adjustments, ensuring optimal conditions for each crop and driving efficiency in resource use. Innovative applications of photoluminescent polymers could also address challenges beyond photosynthetic optimization. For example, incorporating these materials into post-harvest packaging solutions could regulate light exposure, preserving freshness and reducing spoilage during storage and transport.

While the possibilities for PPNCs in agriculture are vast, their successful implementation hinges on addressing cost-related barriers. Ensuring that these technologies are affordable and accessible to farmers is critical for widespread adoption. Balancing the initial investment with long-term benefits, such as reduced reliance on chemical inputs, higher yields, and improved crop resilience, will be essential to drive their integration into mainstream agricultural practices.

In summary, photoluminescent polymers and their nanocomposite counterparts represent a transformative opportunity for modern agriculture that can provide multifunctional applications as shown in Fig. 4.

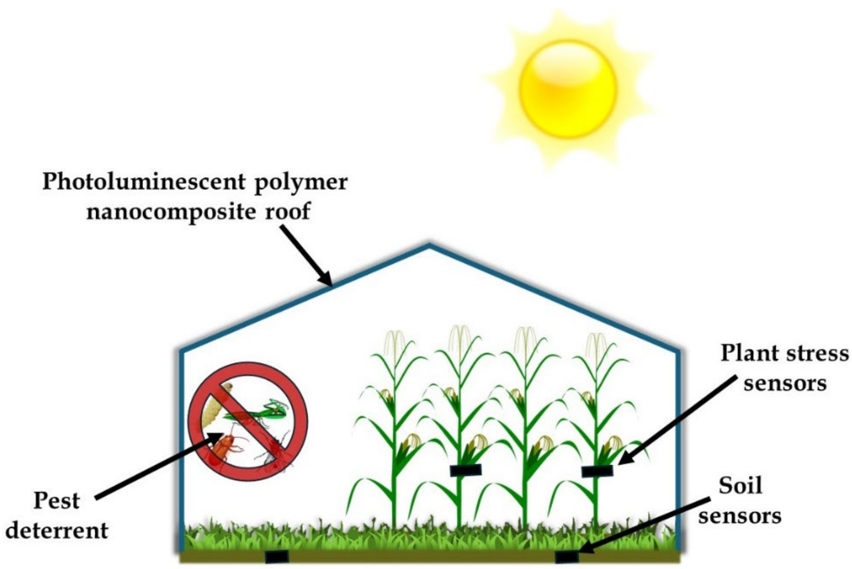

Fig. 4. Expanded applications of photoluminescent polymer nanocomposites

Conclusion

Light plays an important role in photosynthesis, yet its natural variability presents challenges for controlled-environment farming. Photoluminescent polymer nanocomposites (PPNCs) offer an innovative path toward more sustainable and efficient agricultural practices. By converting less-utilized wavelengths, such as ultraviolet and blue light, into plant-friendly spectra, PPNCs enhance the availability of photosynthetically active radiation (PAR). This not only increases photosynthetic efficiency but also supports healthier crops with higher yields, reducing the need for chemical fertilizers and pesticides. The effectiveness of PPNCs relies on both the quality of the photoluminescent materials and the robustness of the polymer matrix. Fabricated using methods like in situ polymerization, solution mixing, and melt blending, these materials have shown notable improvements in plant growth metrics, including biomass production, fruit yield, and crop quality. By enabling resource-efficient and customizable farming solutions, PPNCs are paving the way for precision agriculture. While the potential of PPNCs is immense, further investigation is necessary to create biodegradable polymer matrices and to assess the long-term effects of luminescent materials on soil and plant health. By harmonizing sustainability with productivity, PPNCs represent a promising advancement in agriculture, fostering a resilient future for both farmers and the environment.

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