

## Article

# Nanostructured Ge-Based Glass Coatings for Sustainable Greenhouse Production: Balancing Light Transmission, Energy Harvesting, and Crop Performance

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## Abstract

Greenhouse horticulture is an energy-intensive production system that requires innovative solutions to reduce energy demand without compromising crop yield or quality. Functional greenhouse covers are particularly promising, as they regulate solar radiation while integrating energy-harvesting technologies. In this study, six nanostructured glass coatings incorporating semiconductor-based quantum dots (QDs) and quantum wires (QWs) of Ge and TiN are developed using magnetron sputtering—an industrially scalable technique widely applied in smart window and energy-efficient glass manufacturing. The coatings' optical properties are characterized in the laboratory, and their agronomic performance is evaluated in greenhouse trials with lamb's lettuce (*Valerianella locusta*) and radish (*Raphanus sativus*). Plant growth, yield, and leaf color (CIELAB parameters) are analyzed in relation to spectral transmission and the daily light integral (DLI). Although uncoated horticultural glass achieves the highest yields, several Ge-QD coatings provide favorable compromises by selectively absorbing non-photosynthetically active radiation (non-PAR) while maintaining acceptable crop performance. These results demonstrate that nanostructured coatings can simultaneously sustain crop growth and enable solar energy conversion, offering a practical pathway toward energy-efficient and climate-smart greenhouse systems.

**Keywords:** energy efficient greenhouse; greenhouse coverings; nanostructured glass; Ge quantum dots; sustainable horticulture; agrivoltaics; crop growth



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## 1. Introduction

Global food demand continues to increase, while agricultural production faces growing challenges from climate variability, land scarcity, and rising energy costs. Greenhouse cultivation provides a stable and controlled production system that mitigates weather extremes and ensures reliable yields [1,2]. Plant growth in greenhouses depends on carefully regulated environmental parameters, such as temperature, humidity, CO<sub>2</sub> concentration, and substrate conditions, which require precise climate control [3]. However, greenhouse farming remains highly energy-intensive, particularly in temperate regions where heating, cooling, and lighting account for major production costs [4]. Reducing energy inputs while

maintaining crop productivity is, therefore, a key challenge that can be addressed through optimized greenhouse coverings combined with renewable energy technologies [5,6].

Integrating solar energy systems into greenhouse structures represents an effective strategy for improving sustainability. Agrivoltaics—photovoltaic (PV) systems combined with crop production—maximizes land-use efficiency by enabling simultaneous food and energy generation. This approach is especially valuable in densely populated or agriculturally intensive regions [7]. A variety of PV technologies are available for such systems, including first-generation crystalline silicon, second-generation thin-film modules (such as amorphous silicon, CdTe, and CIGS), and third-generation advanced types (organic, tandem, and perovskite solar cells) [8]. The global installed capacity of agrivoltaic systems has grown exponentially, from 5 MWp in 2012 to about 14 GWp in 2021, currently exceeding 2.8 GWp across more than 200 projects [9].

When applied to greenhouses, PV technologies can be mounted externally or integrated into the roof structure as transparent, semi-transparent, or opaque modules. Solar greenhouse systems, therefore, address both land-use efficiency and greenhouse gas reduction goals [10]. Every PV module alters light transmission, so the success of the technology depends on balancing energy production with sufficient photosynthetically active radiation (PAR) for crop growth [11–14]. Some studies report that shading from PV panels has limited or even positive effects on crop productivity, including improved water-use efficiency and reduced canopy temperature [15]. Semi-transparent PV materials, in particular, allow greater flexibility in managing sunlight while minimizing shading losses.

Plants utilize light within the 400–700 nm range, known as PAR, for photosynthesis. Blue (400–500 nm) and red (600–700 nm) wavelengths play dominant roles, while green (500–600 nm) and far-red (700–750 nm) light contribute to morphology and developmental regulation. Each spectral region influences photosynthesis and photomorphogenesis differently: blue and UV light stimulate pigment and antioxidant biosynthesis; red and far-red light regulate stem elongation and flowering; and green light penetrates deeper into the canopy, supporting photosynthesis in inner leaf layers [16]. Consequently, controlling the spectral composition of transmitted light through greenhouse coverings strongly affects plant growth, yield, and product quality.

Common greenhouse covering materials include plastic films, semi-rigid polymers, and glass, and possess distinct optical characteristics that affect light transmission and crop performance [17]. Among them, glass remains the most durable and highly transparent to PAR [5,18,19]. Recent advances in coating technologies enhance both optical and thermal properties [20–23]. Semiconductor-based thin films containing nanostructures, such as quantum dots (QDs) and quantum wires (QWs), emerge as promising candidates for functional greenhouse glass [18–23]. These nanostructures exhibit quantum confinement and multiple exciton generation, enabling high photovoltaic efficiencies and tunable spectral transmission [24–29].

Magnetron sputtering is an industrially established deposition technique that allows precise control of film thickness and composition. It offers high deposition rates, excellent adhesion, and uniform coatings over large areas, making it suitable for the large-scale production of energy-efficient glass [30].

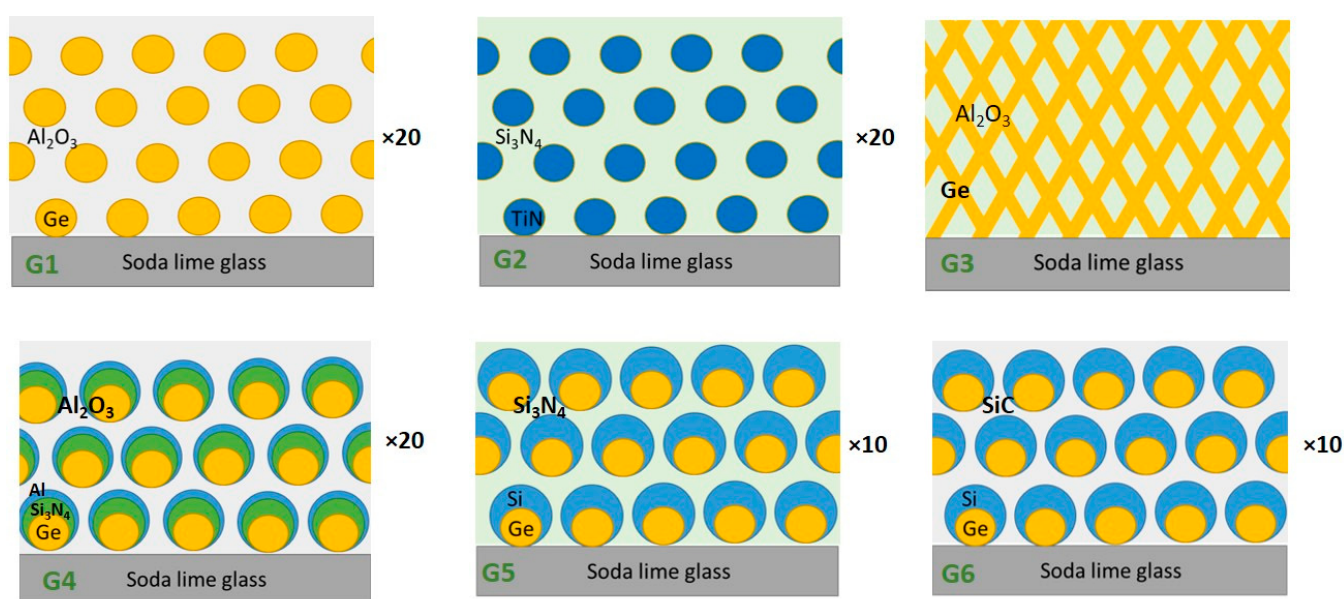
This study investigates six nanostructured glass coatings based on Ge and TiN QDs, Ge QWs, Ge/Si<sub>3</sub>N<sub>4</sub>/Al, and Ge/Si core-shell structures, all deposited by magnetron sputtering. The objectives are as follows: (i) to determine how their optical properties influence the growth, morphology, and yield of lamb's lettuce (*Valerianella locusta*) and radish (*Raphanus sativus*), and (ii) to evaluate whether these coatings balance plant requirements with solar energy conversion potential. The selected materials demonstrate high photoelectric conversion efficiency, industrial relevance, and well-established preparation methods within our

research group. By linking spectral transmission characteristics with plant responses, the study provides insights into the design of advanced greenhouse coverings that support both sustainable crop production and renewable energy generation.

## 2. Materials and Methods

### 2.1. Preparation of Coatings

The thin films used as greenhouse coverings are developed at the Laboratory for Thin Films, Ruđer Bošković Institute (Zagreb, Croatia), using optimized materials for solar energy conversion [24,27–29]. Six distinct nanostructured coatings are fabricated on horticultural glass substrates via magnetron sputtering. These include Ge quantum dots (QDs), TiN QDs, Ge quantum wires (QWs), Ge/Si<sub>3</sub>N<sub>4</sub>/Al, and Ge/Si core-shell QDs, embedded in Al<sub>2</sub>O<sub>3</sub>, SiC, or Si<sub>3</sub>N<sub>4</sub> matrices. The structures of the materials are schematically illustrated in Figure 1.



**Figure 1.** Scheme of structural properties of the thin films used for greenhouse cover.

Magnetron sputtering is selected because it is widely applied in the industrial production of energy-efficient glass and smart windows, ensuring reproducibility and scalability. Deposition parameters are optimized to achieve controlled nanostructure formation, uniform coverage, and stable adhesion to the glass surface. All coatings are produced using a KJLC CMS-18 magnetron sputtering system (Kurt J. Lesker Company GmbH, Dresden, Germany) at substrate temperatures between 300 and 500 °C. Detailed procedures are described in previous studies [24,27–30]. No additional surface treatment is applied to the glass or coatings.

Preparation parameters, including structure, matrix, deposition power, deposition time, and temperature, are summarized in Table 1. Greenhouses G1 and G2 are covered with Ge and TiN QDs embedded in Al<sub>2</sub>O<sub>3</sub> and Si<sub>3</sub>N<sub>4</sub> matrices, respectively. Greenhouse G3 contains Ge QWs in Al<sub>2</sub>O<sub>3</sub>, G4 contains Ge/Si<sub>3</sub>N<sub>4</sub>/Al core-shell QDs in Al<sub>2</sub>O<sub>3</sub>, while G5 and G6 include Ge/Si core-shell QDs embedded in SiC and Si<sub>3</sub>N<sub>4</sub>, respectively. A seventh greenhouse (G7) is covered with standard horticultural soda-lime glass and serves as the control.

**Table 1.** Structural properties of the greenhouse coverings used in the experiment (G1–G7). The thin films with structure specified in column Structure are deposited on glass substrate.  $P$  defines the deposition power while  $t$  defines the deposition time for each element, specified in column Structure; Matrix defines material which holds the nanoparticles (NPs), while  $T$  defines the substrate temperature during the deposition, and  $d$  is the thickness of the film used for coating.

| Glass | Structure                                                                     | $P$ (W)        | $t$ (s)      | Matrix                         | NPs                                   | $T$ (°C) | $d$ (nm) |
|-------|-------------------------------------------------------------------------------|----------------|--------------|--------------------------------|---------------------------------------|----------|----------|
| G1    | (Ge/Al <sub>2</sub> O <sub>3</sub> ) × 20                                     | 10/130         | 45/100       | Al <sub>2</sub> O <sub>3</sub> | Ge                                    | 500      | 82       |
| G2    | ((Ti + Si <sub>3</sub> N <sub>4</sub> )/Si <sub>3</sub> N <sub>4</sub> ) × 20 | (65 + 100)/100 | 15/20        | Si <sub>3</sub> N <sub>4</sub> | TiN                                   | 300      | 156      |
| G3    | Ge + Al <sub>2</sub> O <sub>3</sub>                                           | 20 + 100       | 1800         | Al <sub>2</sub> O <sub>3</sub> | Ge                                    | 400      | 53       |
| G4    | (Ge/Si <sub>3</sub> N <sub>4</sub> /Al/Al <sub>2</sub> O <sub>3</sub> ) × 20  | 25/25/25/140   | 10/40/40/200 | Al <sub>2</sub> O <sub>3</sub> | Ge/Si <sub>3</sub> N <sub>4</sub> /Al | 500      | 82       |
| G5    | (Ge/Si/Si <sub>3</sub> N <sub>4</sub> ) × 10                                  | 10/50/150      | 80/75/15     | Si <sub>3</sub> N <sub>4</sub> | Ge/Si                                 | 500      | 53       |
| G6    | (Ge/Si/SiC) × 10                                                              | 10/50/150      | 80/75/15     | SiC                            | Ge/Si                                 | 500      | 0.0      |
| G7    | Soda–lime glass                                                               | --             | --           | --                             | --                                    | --       | --       |

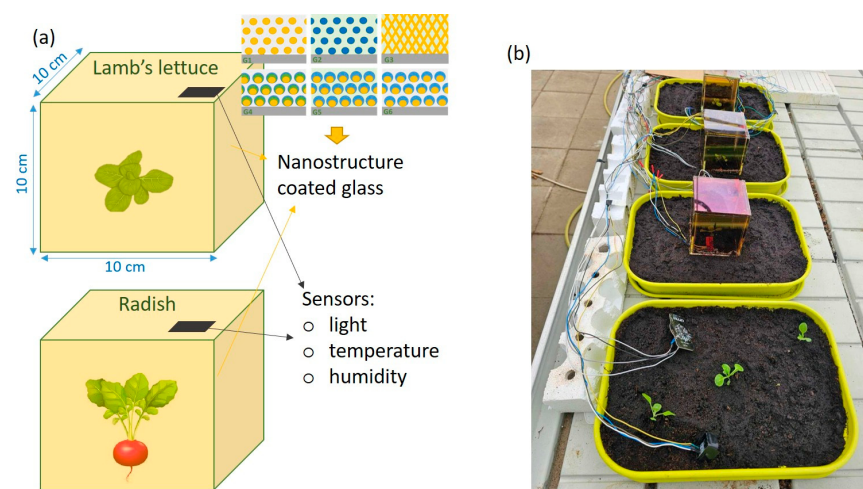
All coatings consist of nanostructures that are several nanometers in size, arranged in three-dimensional lattices. The coating structures are analyzed by grazing incidence small-angle X-ray scattering (GISAXS), as shown in Figure S1 (Supplementary Materials). All materials exhibit strong light-to-electricity conversion properties [25–29].

## 2.2. Optical Characterization

The optical properties of the coated glasses are characterized in the same laboratory using an Ocean Optics spectroscopic system (Ocean Optics B.V., Ostfildern, Germany). The system consists of a deuterium–halogen light source (DH-2000-BAL; 215–2500 nm), a UV/VIS high-resolution spectrometer (HR4000; 190–1100 nm), and SpectraSuite 2.0 software (Ocean Optics, Dunedin, FL, USA) [31].

## 2.3. Greenhouse Experimental Design

The experiment is conducted at the Maksimir Experimental Field (45°49′ N, 16°02′ E) of the University of Zagreb, Faculty of Agriculture, Croatia. A total of eight experimental variants with three replicates are tested: seven glass-covered mini-greenhouses (10 × 10 cm<sup>2</sup> windows, 3 mm thick glass) and one open-field treatment without cover (NG). The experimental setup and a photograph of the greenhouses are presented in Figure 2.



**Figure 2.** (a) Scheme of the greenhouses used for the plant growth. They consist of nanostructure coated glass equipped with sensors for monitoring light transmission properties, temperature, and humidity inside the greenhouse. (b) Experimental realization at University of Zagreb, Faculty of Agriculture, Croatia.

Six greenhouses (G1–G6) are covered with nanoparticle-coated glass, and one (G7) with uncoated soda–lime glass. Microclimatic conditions are continuously monitored inside each greenhouse. Air temperature and relative humidity are recorded using BME280 sensors (Bosch Sensortec GmbH, Reutlingen, Germany), while light spectral distribution is measured via AS7265x sensors (ams-OSRAM AG, Premstaetten, Austria), which detect 18 wavelengths in the 410–940 nm range. Data are logged hourly using a Raspberry Pi 4 Model B (Mouser Electronics, Assago-MI, Italy).

Two vegetable crops are used: lamb's lettuce (*Valerianella locusta* cv. Accent, Enza Zaden, Enkhuizen, the Netherlands) and radish (*Raphanus sativus* cv. Celesta, Enza Zaden, Enkhuizen, the Netherlands). These crops are chosen for their small size, as the coated glass pieces ( $10 \times 10 \text{ cm}^2$ ) limit greenhouse dimensions. Lamb's lettuce seedlings with two to three true leaves are transplanted under the test coverings in late October and harvested after 4 weeks. Radish is then planted in the same greenhouses and harvested five weeks later.

#### 2.4. Plant Morphology and Yield Measurements

Plant morphology is evaluated at harvest. For lamb's lettuce, the measured parameters include number of leaves, rosette (leaf) mass, root mass, and total biomass. For radish, the parameters include number of leaves, hypocotyl diameter, hypocotyl mass, and total biomass.

At harvest, plants are cleaned and weighed using a precision balance (Ohaus Adventurer-Pro AV53; Mettler Toledo d.o.o., Zagreb, Croatia). Biomass is separated into rosette/leaf and root/hypocotyl fractions. Yield per unit area is estimated by multiplying the mean rosette or hypocotyl mass by the standard plant density.

Plant density for lamb's lettuce ( $700 \text{ plants} \cdot \text{m}^{-2}$ ) is calculated based on a sowing density of 7–15 cm between rows and 50–80 seeds per meter [32]. For radish, a density of  $200 \text{ plants} \cdot \text{m}^{-2}$  is used, corresponding to the 2–5 cm spacing within rows and the 10–20 cm between rows [33].

#### 2.5. Leaf Color Analysis

Fully developed leaves are counted, and leaf color parameters are determined using a colorimeter (PCE-CSM 4; PCE Instruments UK Ltd., Southampton, UK) in the CIELAB color space [34]. The following parameters are recorded:  $L^*$  (lightness),  $a^*$  (green–red axis),  $b^*$  (blue–yellow axis), hue angle (H, color tone), and chroma ( $C^*$ , color purity).

#### 2.6. Statistical Analysis

Data are analyzed via analysis of variance (ANOVA), using the PROC GLM procedure in SAS<sup>®</sup> software version 9.3 (SAS Institute Inc., Cary, NC, USA) [35]. Mean values are compared using the least significant difference (LSD) test at  $p < 0.05$ . Different letters in tables or figures indicate statistically significant differences among treatments.

### 3. Results

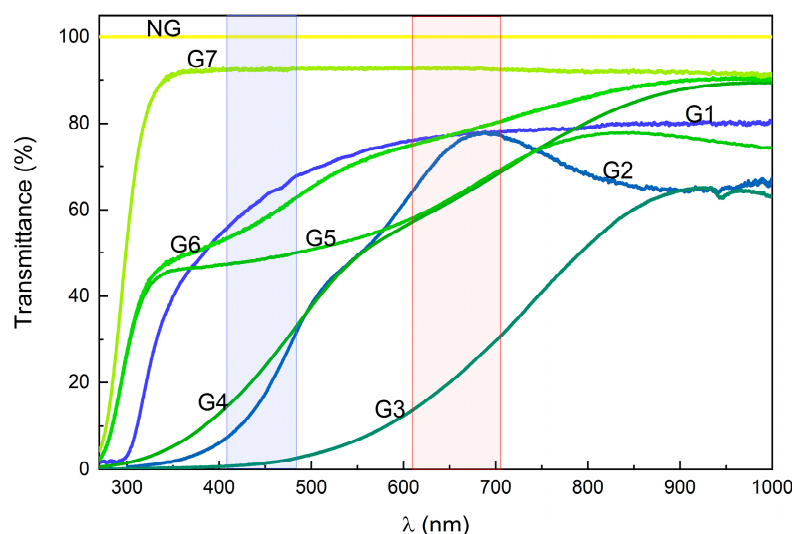
The results are divided into two parts. The first presents the optical properties of the coated glasses and the intensity of transmitted light across different wavelength ranges, measured both in the laboratory and in the field during crop growth. The second part focuses on plant properties and their relationship to the characteristics of the greenhouse coverings.

#### 3.1. Optical Properties of Nanostructured Coatings

##### 3.1.1. Laboratory Results

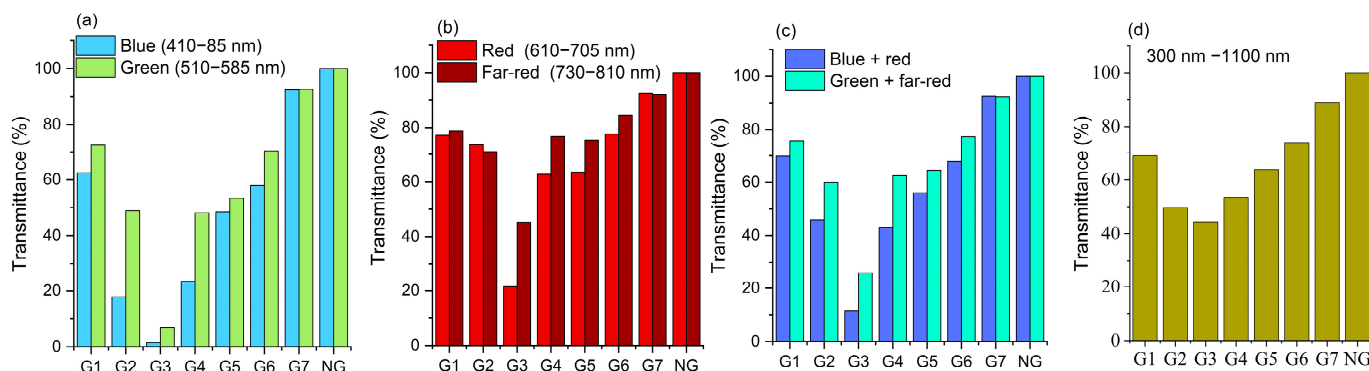
Light transmittance of greenhouse coverings is a key parameter for both plant growth and photovoltaic energy conversion. The spectral transmittance curves of the coated glasses,

standard horticultural glass (G7), and the open field (NG) are shown in Figure 3, with the photosynthetically active regions indicated by shaded areas.



**Figure 3.** Spectral transmittance of greenhouse covering materials. Dashed regions indicate wavelength ranges in blue and red, relevant for chlorophyll absorption (photosynthetically active radiation, PAR).

As illustrated in Figure 3, the tested coatings exhibit distinct spectral characteristics, with transmittance varying strongly across wavelengths. The average transmittance values in key spectral regions are as follows: blue (410–485 nm), green (500–585 nm), red (610–705 nm), and far-red (705–750 nm), which are summarized in Figure 4. The blue and red regions are particularly emphasized due to their relevance to chlorophyll absorption (Figure 4a,b), while green and far-red wavelengths are analyzed separately (Figure 4c). The overall transmittance across the full spectrum (300–1100 nm) is presented in Figure 4d.

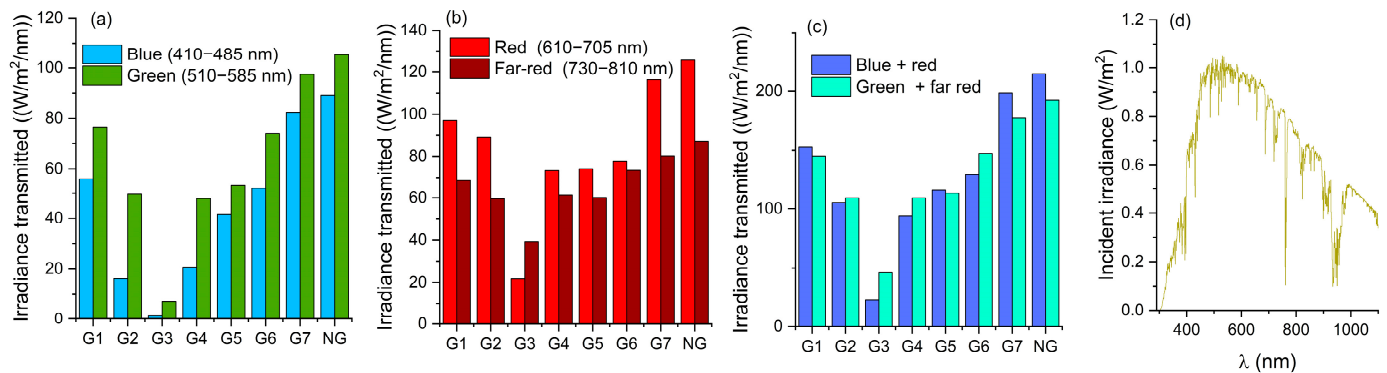


**Figure 4.** Average transmittance of greenhouse coverings (G1–G7, NG) in different wavelength regions: (a) blue and green (410–585 nm), (b) red and far-red (610–750 nm), (c) relative contribution of PAR and non-PAR regions, and (d) average transmittance across the measured spectrum.

Among all coverings, the open-field condition (NG) shows complete transparency (100%), while uncoated horticultural glass (G7) exhibits the highest transmittance among greenhouse materials (92.5% on average). Among the coated variants, G1 achieves the highest mean transmittance (70.79%), whereas G3 records the lowest (9.99%).

Because the used semiconductor materials possess a bandgap above 0.7 eV (Ge bandgap), no significant absorption is expected in the far-infrared region. Therefore, the optical properties of the coated glasses (G1–G6) should remain similar to that of the uncoated glass (G7) for wavelengths above 1800 nm.

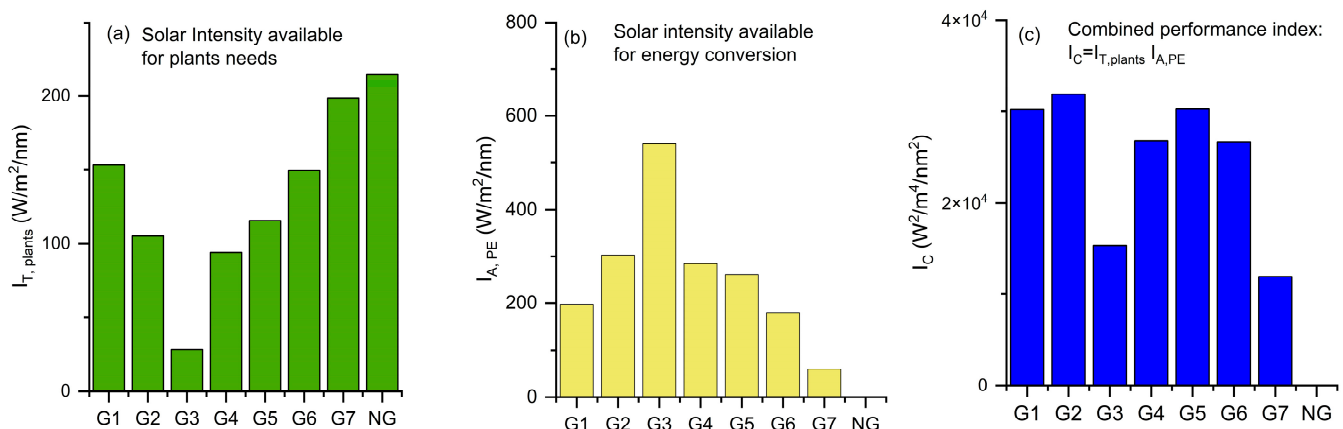
To calculate the intensity of light transmitted into each greenhouse, transmittance data are combined with the solar irradiance spectrum (Figure 5). The transmitted irradiance in the blue–green and red–far-red regions is shown in Figures 5a and 5b, respectively. Figure 5c compares the total photosynthetically active radiation (PAR; blue and red) with non-PAR light (green and far-red), while Figure 5d displays the reference solar spectrum used for the calculations. As expected, G3 records the lowest transmitted irradiance, while NG achieves the highest values.



**Figure 5.** Light intensity transmitted through the tested greenhouse glass coverings, calculated from the transmittance and solar spectrum for different wavelength intervals: (a) blue and green light, (b) red and far-red light, and (c) sum of the intensities of blue and red (PAR), green and far-red (non-PAR) light. (d) Reference Sun’s spectrum used to calculate values for (a–c) panels.

In photovoltaic applications, an ideal covering maximizes transmittance in PAR regions while minimizing it in non-PAR wavelengths, enabling selective absorption for energy generation. This balance is evaluated in Figure 6, which shows (a) transmitted PAR irradiance ( $I_{T, plants}$ ), (b) absorbed irradiance available for photovoltaic conversion ( $I_{A, PE}$ ), and (c) the combined performance index ( $I_C$ ), defined as follows:

$$I_C = I_{T, plants} I_{A, PE} \quad (1)$$



**Figure 6.** Performance indices of greenhouse coverings: (a) irradiance transmitted ( $I_{T, plants}$ ) in the photosynthetically active radiation (PAR) region, (b) irradiance absorbed by the greenhouse available for photovoltaic conversion ( $I_{A, PE}$ ), and (c) combined performance index ( $I_C$ ) calculated as the product of (a,b). Higher values indicate coverings with greater potential to balance crop growth and electricity generation.

According to this index, G2 shows the most favorable performance, followed closely by G1 and G5. In contrast, NG and G7 perform the worst in terms of photovoltaic potential,

since they absorb little to no light. G3 also shows limited overall performance due to its low transmitted light intensity limiting plant growth, despite its high absorption capacity for energy conversion.

### 3.1.2. Field Results

In field conditions, the transmitted light across tested coatings is measured using AS7265x sensors, which detect 18 wavelengths between 410 and 940 nm. Measurements are grouped into the same wavelength intervals as in the laboratory experiments. The recorded irradiance for each wavelength ( $I_\lambda$ ,  $\mu\text{W}\cdot\text{cm}^{-2}$ ) is converted to  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ , according to Leon-Salas et al. [36], allowing for the calculation of the daily light integral (DLI) in  $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  (Table 2).

**Table 2.** The light intensity transmitted to the greenhouse for different wavelength regions and daily light integral DLIs. All values are in  $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for tested glass coverings in field conditions.

| Glass <sup>1</sup> | Blue Light<br>410–485 nm | Green Light<br>510–585 nm | Red Light<br>610–705 nm | Far-Red Light<br>730–810 nm | DLI<br>410–940 nm |
|--------------------|--------------------------|---------------------------|-------------------------|-----------------------------|-------------------|
| G1                 | 5.09                     | 4.15                      | 4.21                    | 6.13                        | 22.37             |
| G2                 | 5.83                     | 4.85                      | 4.75                    | 8.77                        | 25.31             |
| G3                 | 4.11                     | 3.31                      | 2.59                    | 4.96                        | 15.82             |
| G4                 | 2.35                     | 2.2                       | 1.67                    | 2.67                        | 9.55              |
| G5                 | 1.83                     | 1.74                      | 1.27                    | 2.09                        | 7.47              |
| G6                 | 4.77                     | 3.79                      | 2.64                    | 4.29                        | 16.39             |
| G7                 | 6.54                     | 5.66                      | 5.31                    | 10.38                       | 29.26             |
| NG                 | 12.69                    | 10.72                     | 9.71                    | 20.88                       | 56.78             |

<sup>1</sup> G1–G6: nanoparticle-coated glass, G7: standard horticultural glass; NG: no greenhouse applied.

The photon flux ( $\phi$ ) and irradiance ( $I_\lambda$ ) are related by

$$\phi = \int_{\lambda_1}^{\lambda_2} \frac{I_\lambda d\lambda}{E_{ph}(\lambda)} \quad (2)$$

where  $\lambda_1$  and  $\lambda_2$  are the starting and ending wavelength of the region of interest, respectively.  $E_{ph}(\lambda) = hc/\lambda$ , is the photon energy.

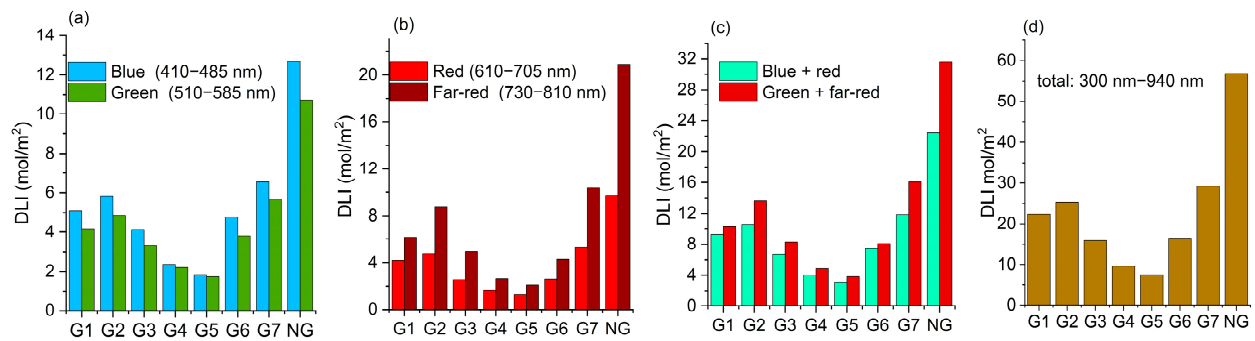
Photosynthetic photon flux density (PPFD), given in  $\text{mol m}^{-2} \text{s}^{-1}$ , is then calculated:

$$Q_{PAR} = \frac{\phi}{N_A} \quad (3)$$

where  $N_A = 6.022 \times 10^{23}$ , (Avogadro's number). Finally, the DLI is obtained by integrating PPFD over the photoperiod of one day:

$$DLI(\text{mol m}^{-2} \text{d}^{-1}) = PPFD(\text{mol m}^{-2} \text{s}^{-1}) \times photoperiod(\text{s}) \quad (4)$$

As shown in Table 2 and Figure 7, nanoparticle-coated glasses differ in transmittivity in a manner consistent with laboratory results. Figure 7a,b show daily photon integrals for blue–green and red–far-red regions, while Figure 7c compares the transmitted PAR (blue–red) and non-PAR (green–far-red) contributions. Figure 7d presents the total DLI, which significantly influences the morphology and yield of lamb's lettuce and radish.



**Figure 7.** Measured number of photons (in  $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) transmitted through the tested greenhouse coverings daily (DLI) for different wavelength intervals: (a) blue and green light, (b) red and far-red light, (c) sum of blue, red (photosynthetically active radiation (PAR) region) and green, far-red (non-PAR) light, and (d) total number of photons transmitted into the greenhouse for wavelength interval 410–940 nm.

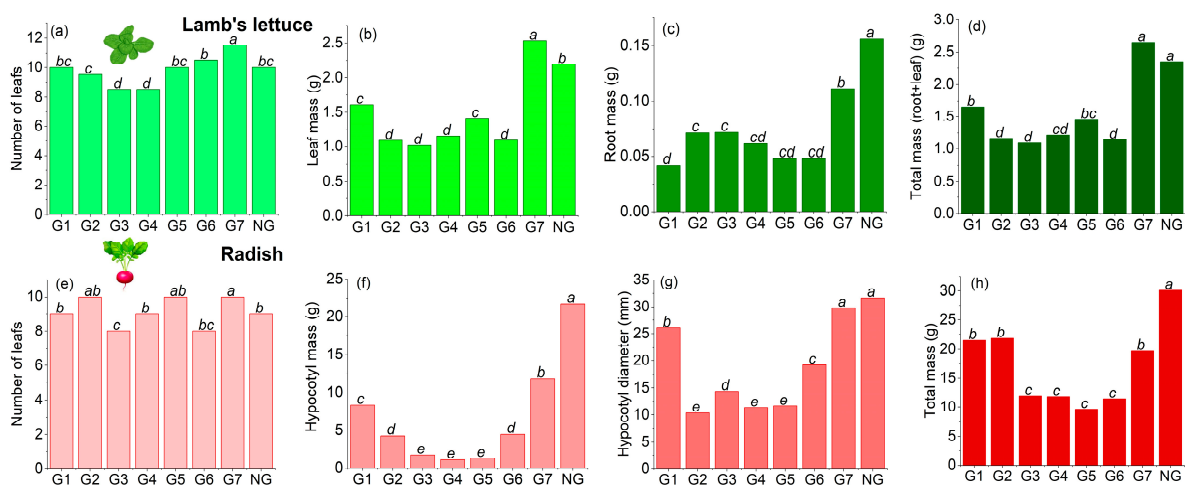
The DLI for the open-field condition (NG) reaches approximately  $56 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ , equivalent to roughly  $2.5 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ . This value is lower than the global average daily insolation ( $\sim 6 \text{ kWh}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ) due to the autumn–winter growing season (October–January) and the site’s geographic position.

Both lamb’s lettuce and radish are low-light crops, capable of growing under less than 6 h of direct sunlight per day. Optimal DLI values are  $8\text{--}12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for lamb’s lettuce and  $12\text{--}15 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for radish, with minimum requirements of 6 and  $8 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ , respectively [37,38]. Thus, even the lowest-transmittance coatings provide sufficient light for the normal growth of both species.

### 3.2. Plant Properties Under Different Coatings

#### 3.2.1. Plant Morphology

Plant morphology varies significantly among coverings. For lamb’s lettuce, biomass, leaf number, and both above- and below-ground mass differ across treatments (Figure 8a–d). The highest values are obtained using standard horticultural glass (G7), except for root mass, which peaks in open-field conditions. Among the coated variants, G1 produces the greatest rosette weight, total biomass, and leaf number, followed by G5.



**Figure 8.** Morphological traits of lamb’s lettuce and radish grown under different greenhouse coverings: (a,e) number of leaves; (b,f) leaf or hypocotyl mass; (c,g) root mass or hypocotyl diameter; and (d,h) total biomass. Results illustrate how spectral properties of coatings influence both shoot and root development. The columns marked with different letters differ significantly at significance level  $p \leq 0.05$ .

Although open-field conditions provide a higher DLI, air temperature and humidity also influence plant development. The glass coverings reduce heat loss, maintaining higher internal temperatures that positively affect morphology and yield.

For radish, growth is the best under open-field conditions (NG) and standard glass (G7). Among the coated treatments, G1 achieves the highest biomass and hypocotyl diameter, while G2 produces the most leaves, and G1 and G2 show comparable total biomass (Figure 8e–h).

The differences among coatings are more pronounced for radish than for lamb's lettuce, particularly with regard to hypocotyl mass (Figure 8h).

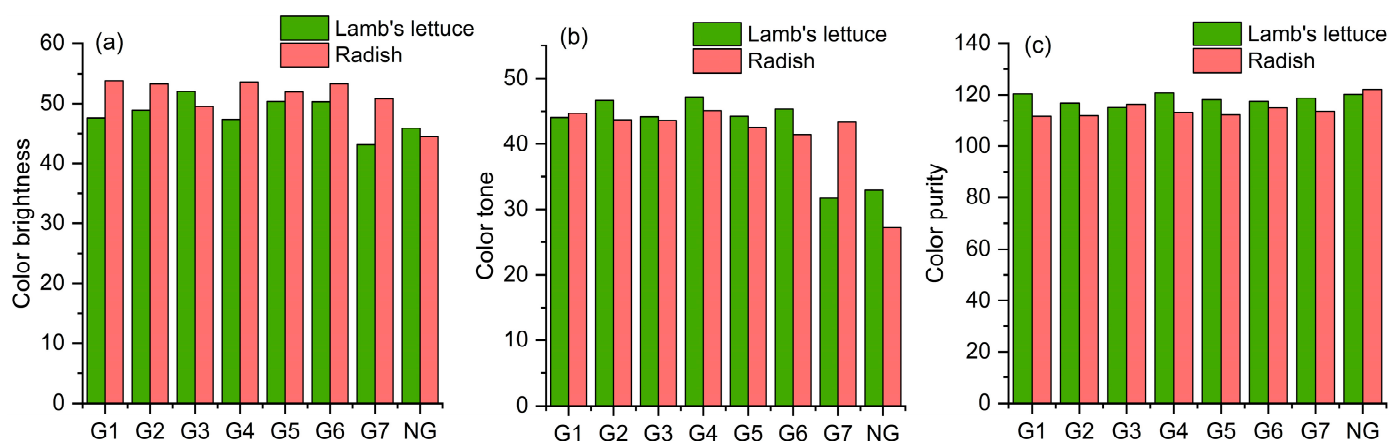
### 3.2.2. Leaf Color

Leaf color parameters (CIELAB) show measurable differences across treatments (Table 3; Figure 9). The L\* value indicates brightness, a\* represents the green–red axis, b\* the blue–yellow axis, while hue (H) and chroma (C\*) denote color tone and purity, respectively [39].

**Table 3.** Color parameters of lamb's lettuce and radish leaves grown under different glasses with Ge-based nanostructures.

| Color               | L*                  |                     | a*                   |                      | b*                  |                      | C*                  |                      | H                     |                      |
|---------------------|---------------------|---------------------|----------------------|----------------------|---------------------|----------------------|---------------------|----------------------|-----------------------|----------------------|
| Glass <sup>1</sup>  | LL <sup>2</sup>     | RD                  | LL                   | RD                   | LL                  | RD                   | LL                  | RD                   | LL                    | RD                   |
| G1                  | 47.60 <sup>c3</sup> | 53.81 <sup>a</sup>  | −22.30 <sup>cd</sup> | −16.29 <sup>ab</sup> | 37.99 <sup>c</sup>  | 41.51 <sup>ab</sup>  | 44.05 <sup>c</sup>  | 44.67 <sup>a</sup>   | 120.40 <sup>ab</sup>  | 111.63 <sup>c</sup>  |
| G2                  | 48.88 <sup>bc</sup> | 53.22 <sup>a</sup>  | −21.06 <sup>c</sup>  | −16.17 <sup>ab</sup> | 41.54 <sup>a</sup>  | 40.56 <sup>abc</sup> | 46.65 <sup>ab</sup> | 43.73 <sup>ab</sup>  | 116.88 <sup>cd</sup>  | 111.86 <sup>c</sup>  |
| G3                  | 52.04 <sup>a</sup>  | 49.53 <sup>b</sup>  | −18.77 <sup>b</sup>  | −19.41 <sup>c</sup>  | 39.97 <sup>ab</sup> | 38.59 <sup>bc</sup>  | 44.16 <sup>c</sup>  | 43.64 <sup>ab</sup>  | 115.15 <sup>d</sup>   | 116.45 <sup>b</sup>  |
| G4                  | 47.38 <sup>c</sup>  | 53.59 <sup>a</sup>  | −24.16 <sup>d</sup>  | −17.77 <sup>bc</sup> | 40.54 <sup>ab</sup> | 41.79 <sup>a</sup>   | 47.19 <sup>a</sup>  | 45.12 <sup>a</sup>   | 120.80 <sup>a</sup>   | 113.18 <sup>bc</sup> |
| G5                  | 50.31 <sup>b</sup>  | 51.95 <sup>ab</sup> | −20.78 <sup>c</sup>  | −16.04 <sup>ab</sup> | 39.03 <sup>bc</sup> | 39.40 <sup>abc</sup> | 44.22 <sup>c</sup>  | 42.54 <sup>bc</sup>  | 118.07 <sup>bc</sup>  | 112.19 <sup>c</sup>  |
| G6                  | 50.29 <sup>b</sup>  | 53.25 <sup>a</sup>  | −20.91 <sup>c</sup>  | −17.56 <sup>bc</sup> | 40.23 <sup>ab</sup> | 37.58 <sup>c</sup>   | 45.36 <sup>bc</sup> | 41.48 <sup>c</sup>   | 117.44 <sup>cd</sup>  | 115.04 <sup>bc</sup> |
| G7                  | 43.07 <sup>d</sup>  | 50.75 <sup>ab</sup> | −15.22 <sup>a</sup>  | −17.39 <sup>bc</sup> | 27.80 <sup>d</sup>  | 39.72 <sup>abc</sup> | 31.72 <sup>d</sup>  | 43.37 <sup>abc</sup> | 118.68 <sup>abc</sup> | 113.61 <sup>bc</sup> |
| NG                  | 45.83 <sup>cd</sup> | 44.48 <sup>c</sup>  | −16.59 <sup>a</sup>  | −14.53 <sup>a</sup>  | 28.41 <sup>d</sup>  | 23.00 <sup>d</sup>   | 32.90 <sup>d</sup>  | 27.20 <sup>d</sup>   | 120.21 <sup>ab</sup>  | 122.26 <sup>a</sup>  |
| LSD <sub>0.05</sub> | 1.6794              | 3.4059              | 1.8626               | 2.4223               | 1.6383              | 2.9954               | 1.4437              | 1.9237               | 2.5045                | 4.1178               |

<sup>1</sup> G1–G6: nanoparticle-coated glass; G7: standard horticultural glass; NG: no greenhouse applied; <sup>2</sup> LL: lamb's lettuce; RD: radish; <sup>3</sup> Values within the column marked with different superscripts differ significantly at significance level  $p \leq 0.05$ .



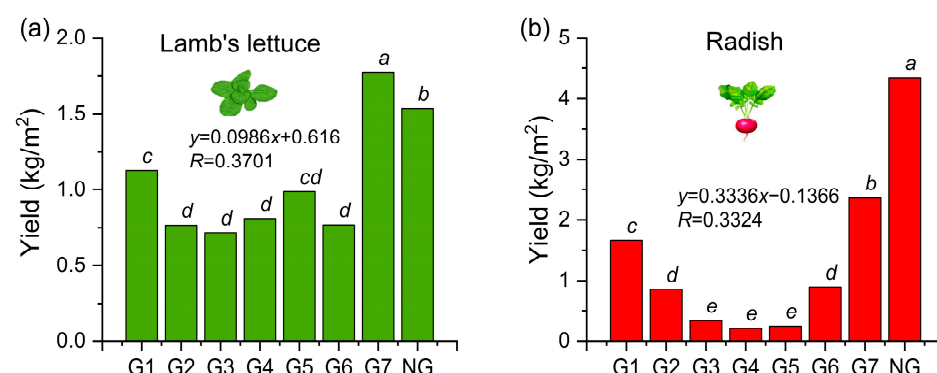
**Figure 9.** Leaf color characteristics of lamb's lettuce and radish measured using CIELAB parameters: (a) color brightness (L\*); (b) color tone (hue angle, H); and (c) color purity (chroma, C\*). Data highlight the impact of glass coatings on chlorophyll-related pigmentation and photosynthetic potential.

The color brightness value (L\*) remains similar across treatments and is often slightly higher under coated glasses than under standard glass or in open-field conditions (Figure 9a). Hue values are significantly lower under G7 and NG (Figure 9b), while chroma (C\*) remains nearly constant among all variants (Figure 9c).

Overall, plants grown under Ge-based nanostructured coatings show minor variations in CIELAB parameters but maintain the color characteristics associated with good market quality. These findings indicate that coatings can modify light spectra without compromising photosynthetic potential or visual quality.

### 3.2.3. Yield

Crop yield is expressed as leaf biomass for lamb's lettuce, and hypocotyl mass for radish (Figure 10). Lamb's lettuce is harvested four weeks after planting, and radish is harvested five weeks later. As shown in Figure S2, air temperature and relative humidity are consistent across treatments, indicating that light spectra are the main factors affecting growth and yield.



**Figure 10.** The yield of (a) lamb's lettuce leaves and (b) radish hypocotyl mass, grown under different glasses with Ge-based nanostructures. The columns marked with different letters differ significantly at significance level  $p \leq 0.05$ .

Maximum yields occur under NG and G7, confirming that uncoated glass provides optimal light for biomass accumulation. However, several Ge-QD coatings maintain yields close to these references while simultaneously absorbing non-PAR. Notably, G1 produces significantly higher yields for both crops than G6, despite similar average transmittance, likely due to differences in spectral selectivity. The higher transmittance of green light (500–600 nm) in G1 may enhance CO<sub>2</sub> assimilation efficiency relative to blue light, contributing to its greater productivity.

Lamb's lettuce yields range from 0.714 to 1.127 kg·m<sup>-2</sup> under nanostructured coatings, compared with 1.771 kg·m<sup>-2</sup> under G7 and 1.540 kg·m<sup>-2</sup> under NG (Figure 10a). Radish yields range from 0.214 to 1.660 kg·m<sup>-2</sup> under nanostructured coatings, compared with 2.362 kg·m<sup>-2</sup> under G7 and 4.344 kg·m<sup>-2</sup> under NG (Figure 10b).

This trade-off between yield and absorbed non-PAR underscores the potential to balance crop productivity with solar energy harvesting, as explored further in the Discussion.

## 4. Discussion

Light not only determines plant growth but also interacts with many other factors, such as air temperature, relative humidity, CO<sub>2</sub> concentration, nutrients, and irrigation. The light environment influences plants through its spectrum, intensity, and photoperiod, since photosynthesis depends on the absorption of photosynthetically active radiation (PAR, 400–700 nm) by chlorophyll pigments. Blue (400–500 nm) and red (600–700 nm) light strongly affect morphology, yield, and quality, while far-red, orange, green, and UVA light also contribute positively, but to a significantly smaller extent [40,41].

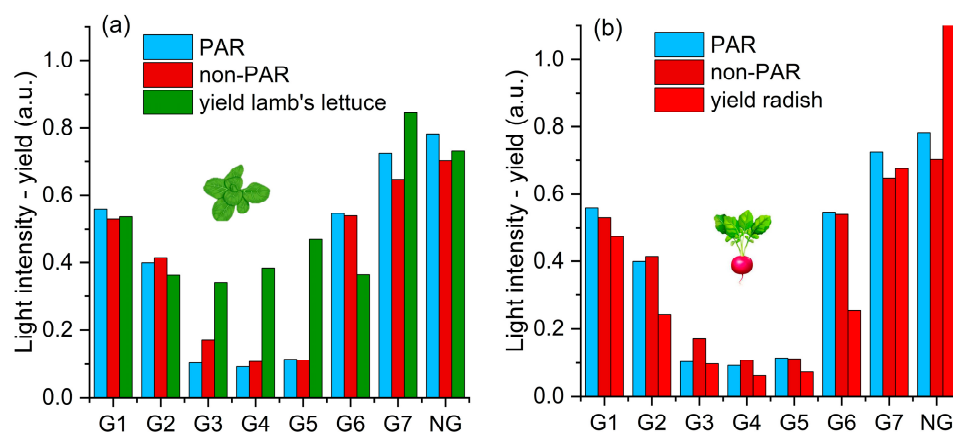
Greenhouse coverings, therefore, play a decisive role in crop outcomes by modifying the transmitted UV, PAR, and NIR fractions of solar radiation [20,42], as well as by interacting with structural and climate-control systems [17,43]. The nanostructured coatings tested

in this study alter spectral transmission in crop-relevant ways and produce clear effects on morphology, leaf color, and yield. These findings are consistent with previous studies showing that spectral composition and the daily light integral (DLI) strongly affect growth [17,44]. In particular, the observed thresholds  $>15 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for radish and  $>20 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  for lamb's lettuce are in accordance with optimal values reported by Avgoustaki et al. and Zha and Liu [45,46], though they are higher than the values determined in other studies [37,38]. Although absolute yields in the autumn–winter trials are lower than those reported in plant factory conditions [47], morphological traits, such as leaf number, hypocotyl diameter, and hypocotyl mass, remain within published ranges [46,47].

Leaf color (CIELAB) analysis further confirms that coatings influence photosynthetic activity. Higher  $L^*$ ,  $a^*$ , and  $b^*$  values indicate higher chlorophyll content and correlate with higher yields, consistent with the previously reported strong links between CIELAB metrics and SPAD/chlorophyll readings [48–51]. Contrary to our results, Cozzolino et al. [52] report higher color parameter values under diffuse greenhouse films compared to clear ones, highlighting that results are context-specific, dependent on the species, growing period, and covering material.

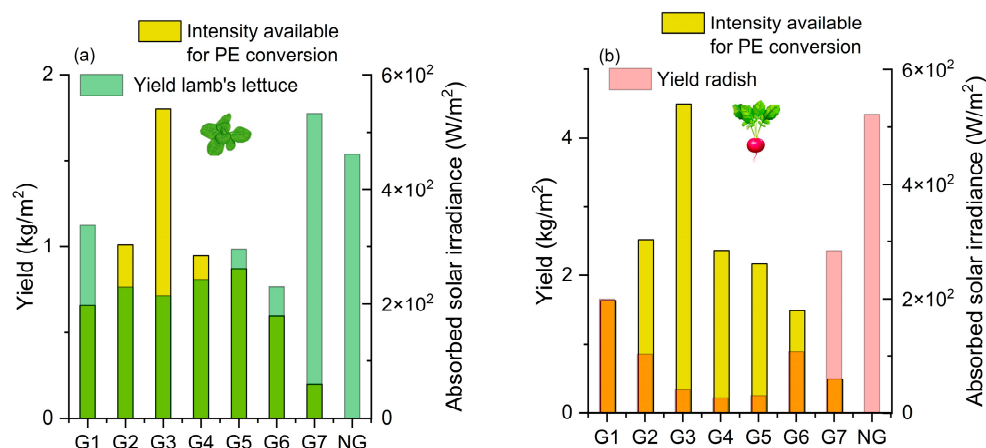
Temperature and relative humidity inside the greenhouses remain relatively similar (variations below 10% of the average), as shown in Figure S2 (Supplementary Material).

Figure 11 illustrates the relationship between transmitted PAR/non-PAR and yield, revealing crop-specific responses. Radish shows an approximately linear dependence of yield on the transmitted PAR, whereas lamb's lettuce displays a nonlinear response; G3, despite its low PAR transmission, achieves about 75% of the biomass of G1 while receiving only around 20% of its PAR. This resilience highlights the importance of the crop-specific optimization of coatings. Given the limited number of plants tested, further large-scale trials are necessary to quantify transmitted light-to-yield ratios more precisely. Additionally, the natural light available during the study period is below average; therefore, higher illumination during spring–summer–autumn is expected to further improve plant quality.



**Figure 11.** Relationship between transmitted light (photosynthetically active radiation, PAR, and non-PAR) and crop yield for (a) lamb's lettuce and (b) radish. Results highlight crop-specific responses, with radish showing a stronger correlation with transmitted PAR, while lamb's lettuce exhibits yield resilience even under reduced light transmission.

Figure 12 compares yield with the solar irradiance available for photoelectric conversion efficiency (PCE). G1 and G2 represent promising compromises for lamb's lettuce, while G1 performs best for radish. G3 is notable for its high PCE potential, with only moderate yield penalties, underscoring its potential for dual-use agrivoltaic strategies.



**Figure 12.** Comparison of solar irradiance absorbed by coated greenhouse glass (available for photoelectric conversion) and crop yield for (a) lamb's lettuce and (b) radish. Results illustrate the trade-off between plant performance and energy-harvesting potential, identifying coatings that balance crop production with renewable energy generation.

Current PV coverings are limited by PAR reduction and low PCE [53], but PCE can increase through QD integration under optimized deposition conditions [27,53]. Seasonal variation also plays a critical role; during spring–summer, both PAR transmission and PCE rise, while reduced transmission, compared to standard horticultural glass, contributes to greenhouse temperature reduction and improved water-use efficiency [54]. High temperatures during late spring, summer, and early autumn typically prevent the cultivation of lamb's lettuce and radish in open-field or greenhouse conditions, as both species quickly transition into the generative phase. Under such conditions, nanoparticle-coated glass, with its lower light transmission, helps mitigate heat stress and enables successful cultivation.

Agrivoltaic systems with ~68% light transmission sustain yields [54], which aligns with our results (Table 3). Although greenhouse energy consumption varies widely, PV greenhouses that produce over 25 kWh·m<sup>−2</sup> per year can fully offset their energy use [22]. Fernández et al. [54] report that PV systems produce around 135 kWh·m<sup>−2</sup> annually, covering 75–114% of energy needs depending on location and system design. Aira et al. [55] find that greenhouses installed with PV systems generate 90.15 kWh while consuming 56.21 kWh, achieving a positive energy balance and self-sufficient greenhouse operation. This indicates that not all greenhouse surfaces need to be covered by PV-active coatings.

Overall, this study demonstrates that nanostructured coatings can selectively absorb non-PAR for energy harvesting while maintaining acceptable crop performance. These findings confirm their potential as functional greenhouse coverings that balance horticultural productivity with renewable energy generation, encouraging further optimization, crop-specific adaptation, and seasonal testing.

## 5. Conclusions

This study demonstrates the potential of nanostructured glass coatings to enhance the sustainability of greenhouse horticulture by combining crop production with solar energy harvesting. Six coatings containing semiconductor-based quantum dots and quantum wires are fabricated via magnetron sputtering, a technique broadly used in energy-efficient glass production, and are systematically evaluated in greenhouse trials with lamb's lettuce and radish.

The results show that plant morphology, yield, and leaf coloration depend strongly on the coatings' spectral properties. While uncoated glass produces the highest yields, Ge-based QD coatings achieve a promising compromise by maintaining acceptable crop

performance while selectively absorbing non-PAR suitable for photovoltaic conversion. This dual function confirms the feasibility of using functional coatings to sustain plant growth and enable renewable energy production.

Nanostructured coatings, therefore, represent a practical step toward smart greenhouse coverings that integrate food production with clean energy generation. The findings provide a foundation for optimizing coating design, scaling-up to commercial greenhouse systems, and advancing climate-neutral agriculture.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15112559/s1>. Figure S1: GISAXS maps of the films used for greenhouse coverings (G1–G6). From the maps, it is possible to obtain the structural properties of the films, including the shape, size, and arrangement of the formed nano-objects. Details are given in Refs. [16,18–20,22]. Figure S2: Average temperature and humidity inside the investigated greenhouses and in the open field conditions.

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## Abbreviations

The following abbreviations are used in this manuscript:

|     |                                     |
|-----|-------------------------------------|
| QD  | quantum dot                         |
| NP  | nanoparticle                        |
| QW  | quantum wire                        |
| T   | transmittance                       |
| PV  | photovoltaics                       |
| PCE | photoelectric conversion efficiency |

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