ACS Sustainable Chemistry & Engineering

pubs.acs.org/journal/ascecg

Research Article

Influence of Plasmonic Thin-Film-Coated Photobioreactors on Microalgal Biomass Composition

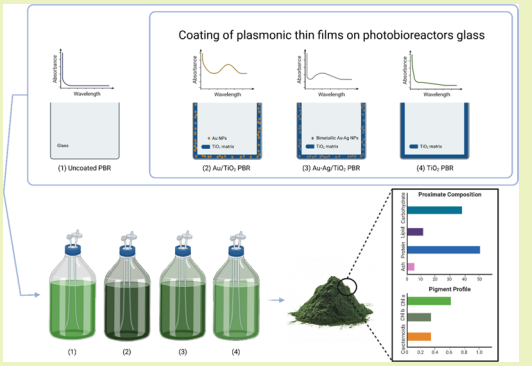
Francisco Pereira, António A. Vicente, Filipe Vaz, Joel Borges,* and Pedro Geada

Cite This: *ACS Sustainable Chem. Eng.* 2025, 13, 791−799

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Microalgae emerge as an eco-friendly solution for food, feed, pharmaceutical, energy, and environmental remediation, providing a diverse range of valuable biocompounds to address the growing global demand. However, light conditions pose substantial challenges, limiting their photosynthetic efficiency and productivity. Light concentration and manipulation provided by plasmonic effects, coupled with photobioreactor technology, may represent a promising solution. This study aimed at evaluating the impact of a new photobioreactor concept on *Chlorella vulgaris* growth and biomass composition. For this purpose, thin films of TiO_2 containing noble metal nanoparticles of Au or Au−Ag, manifesting the phenomenon of localized surface plasmon resonance (LSPR), were directly applied onto photobioreactors' walls. These two thin film systems influenced the profile of transmitted light reaching the microalgal cells, notably reducing its intensity in specific visible regions. The Au/TiO_2 coating caused a marked reduction in the red region with a maximum absorbance peak at 672 nm. On the other hand, the maximum absorbance of the $Au−Ag/TiO_2$ coating was shifted to 642 nm, exhibiting an even broader LSPR band. After 18 days of cultivation, the application of plasmonic thin films did not induce increases in dry biomass nor elevated productivity. However, in general, the quality of the biomass improved considerably, both in terms of protein and pigment profile. Specifically, the utilization of Au/TiO_2 coating resulted in a notable augmentation of 2.1-, 2.4-, and 3.2-fold for chlorophyll *a*, chlorophyll *b*, and carotenoids, respectively. These enhanced values for pigment accumulation highlight the biotechnological potential of this solution.



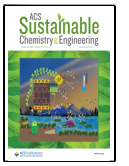
KEYWORDS: *high-value compounds, microalgae, noble metal nanoparticles, thin film coatings, plasmonic-based technology*

1. INTRODUCTION

Microalgae constitute a group of photosynthetic microorganisms capable of growing in various aquatic environments. One of their distinctive attributes is the ability to transform carbon dioxide (CO_2), a relevant greenhouse gas, into biomass, rich in interesting biocompounds (e.g., amino acids, *β*-carotene, lutein, valuable fatty acids).[1,2] These products have relevant characteristics to various biotechnological areas, such as food, energy, pharmaceutical, and cosmetics industries, and even to mitigate current environmental problems.[3]

The growth of microalgae is determined by the interference of abiotic factors such as temperature, salinity, light, and nutrient availability, among others.[1,4] In the context of photoautotrophic growth, light stands out as a primary feature, whether regarding its quantity (intensity and period) and quality (incidence wavelengths), since it can impact cell's physiology and metabolic profile. When microalgae are exposed to different available light intensities, they tend to optimize their photosynthetic machinery. However, increasing light intensity can cause cellular damage and toxic stress through the accumulation of reactive oxygen species (ROS), promoting growth inhibitions.[5−7] On the other hand, when the light intensity is below a certain threshold, photosynthesis is replaced by respiration, and microalgae start consuming oxygen and high-energy compounds to maintain their metabolism.[6,8] During the cultivation of these microorganisms, both natural and artificial lighting sources can be employed. Natural light is usually used in open systems and has been largely limited due to the inefficient solar utilization of microalgae.[2,9] Conversely, artificial light predominantly finds application in closed systems, such as photobioreactors (PBRs).[10] Therefore, optimizing light supply and its distribution in the PBR becomes mandatory to enhance biomass productivity and accumulation of high-value compounds.[11] Microalgae have the capability to utilize specific wavelengths within the natural visible light spectrum (400−700 nm).[10] However, the photosynthetic activity of several

Received: August 1, 2024
Revised: December 24, 2024
Accepted: December 27, 2024
Published: January 8, 2025



ACS Publications

© 2025 American Chemical Society

microalgae is not uniform throughout this spectrum, working well under specific wavelengths, while others may cause photoinhibition.[6,9] In addition, it is also known that wavelengths associated with blue and red lights are optimal for photosynthetic activity.[10] For instance, chlorophylls, the main pigment in algae, use wavelengths between 450−475 nm (blue region) and 630−675 nm (red region).[9,12,13] Other pigments commonly present in microalgae biomass, such as carotenoids and phycobiliproteins, absorb light within the range of 450−550, and 500−650 nm, respectively.[9,12]

Considering the key role played by light exposure on photosynthetic microorganisms' growth as microalgae, there is a demand for innovative technologies to enhance production rates, for example, by reducing wasted radiation. One potential approach to optimize the quality and quantity of light arriving to PBRs is by implementing thin film coatings, such as those manifesting the LSPR phenomenon.[14,15] LSPR excitations are characterized not only by the absorption and scattering of light (e.g., important to tune the color[16]), but also by the enhancement of electromagnetic fields near the plasmonic nanoparticles (NPs). The latter effect is particularly important for plasmon-enhanced phenomena.[14] LSPR behavior is strongly dependent on the type of metal, as different materials have different dielectric functions, originating resonance bands in different wavelengths. Some characteristics of the LSPR band can be measured by an absorbance spectrum, and both the band maximum and shape depend on the size, shape, and interparticle distance of the nanoparticles, as well as on the surrounding dielectric medium.[8,15,17] This means that the optical properties of plasmonic noble metal nanoparticles can be tuned from near-ultraviolet to near-infrared colors,[16] offering the possibility to tailor light intensity and wavelength in the context of microalgae growth. In particular, plasmonic effects can lead to enhanced light extinction, either by absorption in resonant wavelengths or by amplification of scattered light at specific wavelengths, contingent of the nature of the employed NPs.[15] In this work, noble metal NPs, like gold (Au) and silver (Ag), are highlighted as they offer the possibility of tuning the LSPR band position within the visible spectrum, i.e., in spectral regions that are critical for microalgae growth. Au and Ag NPs have historically been the most used noble metals in several applications, from stained-glass windows in medieval cathedrals to modern sensing and surface-enhanced plasmonic phenomena.[18] Au NPs present some important properties: inert nature and stability, biocompatibility, and poor toxicity. In turn, Ag NPs reveal higher extinction cross sections (i.e., higher absorption and scattering efficiencies), yet they are more prone to oxidation and manifest lower biocompatibility. In fact, as verified in previous works, thin films containing solely Ag NPs suffer from degradation when in contact with acidic/basic environments, while the Au-containing and TiO_2 thin films maintain their optical properties.[19] Therefore, the synergistic combination of Au and Ag NPs in bimetallic systems may offer several advantages. Combining Au and Ag in bimetallic systems may improve the chemical and thermal stabilities of single Ag NPs, preventing oxidation and enabling biocompatibility. This leads to electromagnetic and scattering enhancements that may enable improved metabolic activity in photosynthetic microorganism, as suggested by very few works in the literature.[20−22] Though, its impact on the accumulation of pigments and synthesis of proteins and lipids has not been widely studied.

The present study was conducted in order to implement and evaluate a novel concept in plasmonic-based technology: a "plasmon-enhanced photobioreactor". This technology differs from those reported in the literature, since the deposition of plasmonic films is done directly on the cylindrical inner glass walls of PBR using a physical vapor deposition (PVD) technique as in this case reactive magnetron sputtering. PVD coatings are recognized as a low environmental footprint deposition process, which eliminates the need for liquid solvents or hazardous materials, resulting in the emission of no pollutants or residues into the environment during coating application. A comprehensive understanding of the effect of different plasmonic thin film coatings (from gold to gold−silver alloy, embedded in a chemical-resistant TiO_2 matrix), on the productivity of microalgal biomass and synthesis of metabolites was carried out. The impact of thin films' metal nanoparticle composition on their optical response when in direct contact with microalgae cultures was determined as well.

2. MATERIALS AND METHODS

2.1. Preparation of the Thin Film Coatings on Reactor's Inner Walls. Reactive magnetron sputtering was used to deposit nanocomposite thin films directly onto the inner (glass) walls of photobioreactors (PBRs). The PBRs have a semicylindrical shape, with 50 mL volume (see Figure S1 in the Supporting Information). The deposited thin films are composed of gold (Au) and gold−silver (Au−Ag) alloys embedded in titanium dioxide (TiO_2). A TiO_2 thin film was also deposited for comparison as a control. This material revealed outstanding chemical stability in preliminary experiments while creating a robust plasmonic system, by protecting the noble metal nanoparticles. The deposition conditions used were optimized in a previous work.[19] Three-quarters of a noble metal disk (total area, 12 mm^2) was symmetrically placed in a rectangular titanium (Ti) sputtering target (200 × 100 × 6 mm^3, 99.99% purity). The noble metal area varied between 12 mm^2 of gold, to prepare Au/TiO_2, and individual pellets of gold and silver (8 and 4 mm^2, respectively) to obtain bimetallic Au−Ag/TiO_2 with a proportion, Au/Ag, of 1:1.[19] The deposition time was adjusted to obtain thin films with a thickness of about 50 nm based on cross-section images from previous studies. During sputter deposition, the plasma was composed of Ar (working gas, partial pressure of 3.8×10^{-1} Pa) and O_2 (reactive gas, partial pressure of 3.6×10^{-2} Pa). The deposition process was performed with a base pressure below $6.0 \times 1 \times 10^{-4}$ Pa, while the DC current density was set to 75 A m^{-2}.

After sputter deposition in the inner bottom and lateral faces of the semicylinders, the coated PBRs were subjected to a thermal annealing treatment, at atmospheric pressure, in a programmable in-air muffle furnace. The selected temperature was 400 °C to promote the formation and growth of NPs throughout the TiO_2 matrix, with adequate size distributions to manifest the LSPR behavior, as demonstrated in previous works.[19]

2.2. Optical Response of the Thin Film Coatings. The optical transmittance of the coated PBRs was measured in the bottom face of the semicylinders to study the LSPR behavior. A conventional spectrophotometer (Shimadzu UV-2450, wavelength range 300−900 nm) was used for the measurements. The optical transmittance spectra (T%) were processed and converted into absorbance (A) values, through the well-known relation, $A = -\log(T\%/100)$.

2.3. Growth of *Chlorella vulgaris* in PBRs Coated with Plasmonic Thin Films. *2.3.1. Microalga Strain and Culture Condition.* The freshwater *C. vulgaris* (Culture Collection of Algae and Protozoa, U.K. strain 211/11B) was used for cultivation under photoautotrophic conditions. This strain was maintained in T25 cell culture flasks (20 mL, containing 18 mL of a growth medium composed by the following composition (mg·L^{-1}): 1.1 $(NH_2)_2CO$, 237 KH_2PO_4, 204 $MgSO_4.7H_2O$, 40 $C_{10}H_{12}O_8N_2NaFe$, 88 $CaCl_2$, 0.83 H_3BO_3, 0.95 $CuSO_4.5H_2O$, 3.3 $MnCl_2.4H_2O$, 0.2

https://doi.org/10.1021/acssuschemeng.4c06367
ACS Sustainable Chem. Eng. 2025, 13, 791−799

$(NH_4)_6Mo_7O_{24}.4H_2O$, 2.7 $ZnSO_4.7H_2O$, 0.6 $CoSO_4.7H_2O$, and 0.014 $(NH_4)VO_3$).[23]

2.3.2. Experimental Setup. The 50 mL PBRs coated with different plasmonic thin films were used to grow *C. vulgaris*. Agitation during cultivation of microalgae was provided by bubbling CO_2-enriched air (1% v/v) at the bottom of the PBR by using a system attached to the bioreactor lid. The flow rate of the air/CO_2 mixture was set at 0.1 L·min^{-1} to support the photosynthesis and assist in the removal of photosynthetically produced O_2. This aeration system consisted of two mass flow controllers that determined the flow rates of air and CO_2 to be supplied to the system. These gases were filtered before being injected into each PBR. Two setups of white light-emitting diodes (LEDs) were used to illuminate the cultures from two directions (0 and 90° angles relative to the PBRs) at an irradiance level of 65 μmol m^{-2} s^{-1}, measured by a LI-250 Light Meter with a LI-190 quantum sensor (LI-COR). The growth medium used in the trials was the formulation described in the previous section (Section 2.3.1). The initial microalgal concentration was the same for all conditions: optical density (OD) of 0.1, corresponding to a biomass concentration of 0.08 g·L^{-1}. A sample was taken every 2 days to monitor the growth of the cultures and to control the pH within a range from pH 7 to pH 8, by adding 1 N HCl or 5 N NaOH whenever necessary. Upon reaching the stationary phase, the cultures were centrifuged at 6000 rpm for 20 min (Heraeus Multifuge X3R Refrigerated Centrifuge, Thermo Fisher Scientific Inc.) and the pellet was frozen (−20 °C) for subsequent lyophilization.

2.4. Growth Measurement and Biochemical Analysis. *2.4.1. Growth Kinetics.* Microalgae growth was monitored by OD measurements at 750 nm and used for dry weight estimation (X, g·L^{-1}) according to eq 1, which represents the calibration curve:

$$X = (0.70 \pm 0.02) \times OD_{750} + (0.00 \pm 0.03) \quad (R^2 = 0.99) \tag{1}$$

Dry cell weight was measured by gravimetric determination, where 10 mL of culture were filtered using a preweighted glass filter paper (VWR, Lisbon), washed with an equal volume of distilled water, and dried at 105 °C for 24 h. Biomass productivity (P, g·L^{-1}·d^{-1}) was used to analyze the performance of microalgae cultures subjected to the different plasmonic films tested, being obtained by eq 2. x_1 and x_2 are the biomass concentrations at time points t_1 and t_2, respectively.

$$P = (x_1 - x_2)/(t_1 - t_2) \tag{2}$$

2.4.2. CO_2 Biofixation. CO_2 fixation rate (R_{CO_2}, g CO_2 L^{-1} d^{-1}) was calculated using an equation (eq 3) as reported.[4] C_C, P, M_{CO_2}, and M_C are the average carbon content (using a value reported for this specific strain[24]), the biomass productivity, and the molar weights of CO_2 and elemental carbon, respectively.

$$R_{CO_2} = C_C \times P \times M_{CO_2}/M_C \tag{3}$$

2.4.3. Determination of Major Chemical Constituents of Microalgae Cells. Total proteins were extracted using sodium hydroxide, NaOH, and determined using the Lowry method.[25] A mass of 10 mg of freeze-dried biomass was subjected to a 100 °C bath for 10 min with 5 mL of NaOH (0.4 N). Cell fragments were then centrifuged at 6000 rpm for 10 min. A volume of 1.25 mL of Lowry's reagent was added to 0.5 mL of the sample resulting from the extraction process followed by the addition of 0.25 mL of Folin's reagent with incubation time of 10 and 30 min in dark condition, respectively. The resulting mixture was measured at 750 nm in a 96-well plate using a SynergyTM HT Multi Detection Microplate Reader (BioTek Instruments, Inc.).

Total lipids from lyophilized biomass were determined through a gravimetric analysis, using a modified method of Bligh and Dyer.[26] A volume of 1 mL of a mixture of the solvent's dichloromethane and methanol (2:1 v/v) was added to 10 mg of biomass. The organic phase was pipetted into preweighted glass tubes, and the residual biomass was reextracted 4 more times until the supernatant showed no pigmentation. After these steps, the resulting organic phase was dried in a stream of nitrogen and then dissolved in a mixture of dichloromethane, methanol, and distilled water using a ratio of 2:1:0.75. The organic phase resulting from this dissolution was subsequently transferred using a pipet into another glass beaker and subjected to a stream of nitrogen again for final weighing.

Total ash content was determined gravimetrically by incineration of 30 mg of biomass over 8 h at 550 °C using a muffle furnace (Nabertherm N3P, Lilienthal, Germany).[26]

Carbohydrates were considered as the remaining mass, and their estimation was determined by subtracting the percentage content of proteins, lipids, and ashes from 100%.

All contents were expressed as a percentage per dry weight.

2.4.4. Pigments Quantification. Methanol was used to chemically disrupt the cells for total extraction of pigments—chlorophylls *a* and *b* and carotenoids—based on a procedure described by Sousa et al.[25] Methanolic pigment extracts were obtained using 10 mg of lyophilized biomass and resuspended in 1 mL of the solvent. Pigments extraction was assisted by thermal hydrolysis at 45 °C for 30 min. After treatment, the supernatant was recovered by centrifugation at 12,000 rpm for 5 min in a microcentrifuge (Mikro 120, AndreasHettich GmbH & Co.KG, Germany). A volume of 200 μL of extract was measured in a 96-well plate using a SynergyTM HT Multi Detection Microplate Reader (BioTek Instruments, Inc.) at specific wavelengths, according to the following equations:

$$\text{chlorophyll } a(\mu g/L) = 16.72 \times \text{Abs}(665\text{ nm}) - 9.16 \times \text{Abs}(652\text{ nm}) \tag{4}$$

$$\text{chlorophyll } b(\mu g/L) = 34.09 \times \text{Abs}(652\text{ nm}) - 15.28 \times \text{Abs}(665\text{ nm}) \tag{5}$$

$$\text{carotenoids}(\mu g/L) = \frac{1000 \times \text{Abs}(470\text{ nm}) - 1.63\ \text{Chl}\ a - 104.96\ \text{Chl}\ b}{221} \tag{6}$$

2.5. Statistical Analysis. All data were expressed as mean ± standard deviation, calculated from three biological replicates, and used in the corresponding graphs and tables. Statistical evaluations were performed using GraphPad Prism 9.0.0 software (Dotmatics, U.K.). The significance of these data was tested by one-way ANOVA, followed by Tukey's multiple comparison test, with significantly different values corresponding to $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Chemical Composition and Optical Response of the Plasmonic Thin Film Coatings. The PBRs were coated with different sets of thin films: Au/TiO_2 and Au−Ag/TiO_2, and with the TiO_2 matrix without plasmonic NPs. The atomic concentration of noble metal elements (Au, Ag) dispersed in the TiO_2 matrix was determined in a previous work, using proper substrates to be evaluated by the Rutherford Backscattering Spectrometry (RBS) technique.[19] Top-view SEM images of the films are presented in Figure S2 in the Supporting Information. For the Au/TiO_2 thin film system, the noble metal content was estimated at 16.7 ± 0.5 at. %, whereas the deposited Au−Ag/TiO_2 thin film revealed atomic concentrations of 8.6 ± 0.5 at. % for Au and 9.1 ± 0.5 at. % for Ag, having an Au/Ag atomic ratio very close to 1. As reported in the literature, thin films containing only Ag NPs suffer oxidation more easily and are degraded when in contact with adverse environments. On the other hand, the annealing treatment enhances Ag diffusion, leading to the formation of NP structures at the film's surface, making Ag NPs even more susceptible to oxidation and degradation.[19] In this sense, using nanocomposite films can significantly enhance the stability, preventing oxidation under harsh conditions, and the presence of Ag in bimetallic Ag−Au NPs can improve and tune the plasmonic properties since localized surface plasmons in Ag

https://doi.org/10.1021/acssuschemeng.4c06367
ACS Sustainable Chem. Eng. 2025, 13, 791−799

NPs are excited at lower wavelengths than in Au NPs, and hence, differences in excitation wavelengths between Ag and Au NPs can be achieved.

As shown in Figure 1, the Au/TiO_2 thin film has a maximum absorbance at about 672 nm, yet the LSPR band is relatively

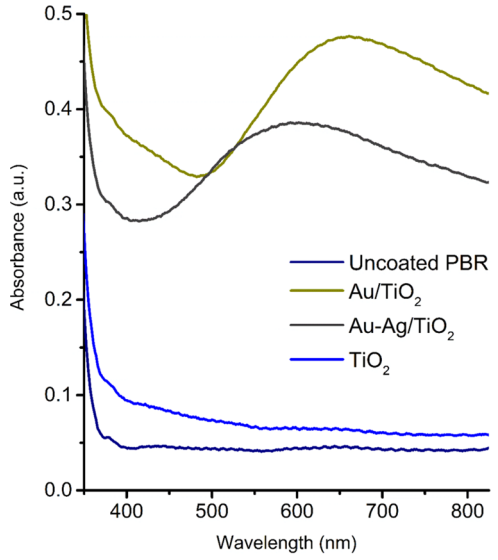


Figure 1. Optical absorbance spectra of the uncoated PBR, and for coated PBRs, using Au/TiO_2, Au−Ag/TiO_2, and TiO_2 thin films.

broad with a full width at half-height (fwhh) of 292 nm. Regarding the Au−Ag/TiO2 thin film, a 30 nm blue shift of the LSPR band, for 642 nm, is clearly observed, while maintaining a relatively large resonance band, with fwhh of 367 nm. According to the optical analysis, two different effects are expected to rule the growth of microalgae and production of metabolites, namely, the (i) selective incidence of different wavelengths and (ii) near-field enhancement in the vicinity of the Au, or Au−Ag NPs.

3.2. Effect of Different Plasmonic Thin Film Coatings on Microalgal Biomass Production. Experiments were conducted to assess the growth of *C. vulgaris* under varying noble metal NPs content − Au/TiO_2, Au−Ag/TiO_2, and also the TiO_2 matrix (for control purposes), all applied onto the inner glass walls of the PBRs. Microalgal growth parameters, such as biomass productivity, maximum cell concentration, and specific growth rate, were calculated and are presented in Table 1. Moreover, CO_2 biofixation was determined and is also displayed in Table 1.

For the various parameters calculated, the uncoated reactor exhibited higher values for productivity, maximum cell concentration, and CO_2 biofixation, according to the values presented in Table 1. On the other hand, the reactor coated exclusively with the TiO_2 matrix showed the highest value for the specific growth rate. The condition with the lowest results in all parameters was the Au/TiO_2-coated PBR. However, the results presented in Table 1 lacked statistical significance when all coated PBRs are compared among them, and with the uncoated PBR ($p > 0.05$). This means that even if the overall absorbance spectrum (range 400−800 nm) of plasmonic PBRs clearly increases from values lower than 0.1 (a.u.) to 0.3−0.5 (a.u.) when compared to TiO_2 and uncoated PBR, the growth-related parameters do not significantly change, considering the statistics of three replica.

According to the literature, optimal microalgal growth requires light in two spectral regions, namely blue and red. Microalgae contain various pigments, such as chlorophyll *a* and *b* and carotenoids, which are responsible for absorbing light during photosynthesis. Chlorophyll *a* primarily absorbs light in the blue and red regions of the visible spectrum, whereas chlorophyll *b* absorbs light mostly in the blue and orange wavelengths. On the other hand, carotenoids, another important group of pigments, absorb light mainly in the blue and green regions.[13,27] The incorporation of these plasmonic thin films made it possible to absorb (and scatter) light at specific wavelengths, especially in those where the localized surface plasmons are excited, restricting light incidence at certain wavelengths to microalgae, particularly those with longer wavelengths. The condition with Au NPs (Au/TiO_2 thin film) showed a single maximum peak near 672 nm, with a bandwidth to cover the red region. On the other hand, the condition with the bimetallic NPs also showed a single maximum peak but shifted to a lower wavelength of 642 nm, with a bandwidth to cover the orange regions. Nevertheless, the results indicate that the incorporation of plasmonic thin films on the PBR surfaces did not induce significant effects, maintaining the same level of biomass production. As reported in very few related works in the literature, the use of different types and shapes of Ag, Au NPs (spheroidal, or nanorods -NRs) creates relatively narrow scattering peaks that can be adjusted to target precise wavelength regions through the manipulation of metal NPs composition and geometry.[28] In the work reported by Eroglu et al.,[28] colloidal NPs of Ag, Au−Ag, and Au were used for the growth of *C. vulgaris*, using LSPR peaks in different regions, namely at 404 nm (Ag NPs), 642, 662, 710 nm (Au NRs) and colloidal mixtures of Ag NPs and Au NRs to reach double resonances. However, the authors only studied the pigment accumulation and not the growth parameters as those presented in the present work (Table 1). However, it is worth noting that one major difference is that the NPs (and NRs) were prepared via chemical synthesis, being in solution and not in contact with the cultures, requiring an outer flask where the main PBR is inserted. This differs from the PBRs design discussed in the present work, where the

Table 1. Biomass Productivity (P, in $g{\cdot}L^{-1}{\cdot}d^{-1}$), Maximum Cell Concentration (X_{max}, in $g{\cdot}L^{-1}$), Specific Growth Rate (μ, in d^{-1}), and CO_2 Biofixation (in $g_{CO2}{\cdot}L^{-1}{\cdot}d^{-1}$) Determined for *C. vulgaris* Grown in the Different PBRs Tested[a]

	P ($g{\cdot}L^{-1}{\cdot}d^{-1}$)	X_{max} ($g{\cdot}L^{-1}$)	μ (d^{-1})	CO_2 biofixation ($g_{CO_2}{\cdot}L^{-1}{\cdot}d^{-1}$)
uncoated reactor	0.33 ± 0.03[a]	5.45 ± 0.32[a]	0.33 ± 0.02[a]	0.71 ± 0.05[a]
Au/TiO_2	0.29 ± 0.01[a]	4.18 ± 0.15[a]	0.32 ± 0.03[a]	0.62 ± 0.03[a]
Au−Ag/TiO_2	0.29 ± 0.01[a]	5.03 ± 0.25[a]	0.33 ± 0.04[a]	0.63 ± 0.02[a]
TiO_2	0.32 ± 0.02[a]	5.30 ± 0.29[a]	0.35 ± 0.04[a]	0.68 ± 0.04[a]

[a]The values are represented as mean ± standard deviation ($n = 3$). Different letters within the same column mean conditions with statistically significant differences ($p < 0.05$) ($n = 3$).

https://doi.org/10.1021/acssuschemeng.4c06367
ACS Sustainable Chem. Eng. 2025, 13, 791−799

plasmonic NPs are sputter-coated into the inner walls of PBRs, and remain in contact with the cultures, allowing an interaction with enhanced electromagnetic fields. In the following section, the performance of the presented PBRs will be compared regarding pigments accumulation.

Another important investigation, performed by Ooms et al.,[29] involved testing Au nanostructures by applying a substrate with nanodiscs (single maximum peak of 623 nm) to stimulate the plasmonic effect via light backscattering using resonance wavelengths, at the bottom of the culture. Their findings indicated a slight increase in the growth rate for *Synechococcus elongatus*. However, there are several differences to point out between that work and the present work. To start, (1) the study was performed in minireactors and the configuration is different. They have used scattered light from LSPR to enhance the growth of photosynthetic microorganisms, while in the present work, the thin film/PBR wall is between incident light and the culture. Therefore, longer wavelengths are being suppressed, since the Au and Ag−Ag NPs embedded in the TiO_2 thin film have enhanced light extinction (absorption + scattering) near 672 and 642 nm, respectively. Other important differences to report are (2) the use of another photosynthetic microorganism (a cyanobacteria) with light capture made essentially by two chromophores, chlorophyll *a* (like *C. vulgaris*) and phycocyanin; (3) supply of an air mixture enriched with 5 times more CO_2; (4) the NPs are not in contact with the cultures, so near-field phenomena cannot occur; and (5) the growth was only monitored for the first 2 days, with the authors drawing conclusions solely from observations made during this early growth period. In contrast, the present investigation comprehensively monitored the entire growth trajectory, providing insights into the influence of employing plasmonic thin films, not only during the lag phase but also throughout the exponential phase. In this context, different variables related to cultivation conditions and increases in the PBR volume induce different growth dynamics. It is therefore crucial to implement conditions that favor and more closely resemble the characteristics observed in large-scale cultivation. However, it is also imperative to highlight the robust stability of the plasmonic thin films developed in this work after various growth processes and sterilizations via autoclaving, showing no signs of degradation as their optical response (absorbance spectra) remains unchanged. Moreover, it is crucial to emphasize the environmental advantages of this type of coating. The reutilization factor becomes particularly advantageous, as the coating can be reused multiple times (based on the durability of the thin film across multiple experimental repetitions), involving only a thin layer (about 50 nm) deposited on the surface of the reactors. In contrast, when colloidal NPs are used, their reuse may become impractical, presenting challenges from both environmental and industrial perspectives.

3.3. Effect of Plasmonic Films on Microalgal Biomass Composition. The characterization of biomass produced in plasmonic thin-film-coated PBRs is essential for understanding the impact of these films on growth, metabolism, and quality of biomass. Plasmonic thin films can modulate the light environment around the microalgae, thereby influencing the synthesis of key biochemical compounds, such as pigments, proteins, and lipids, all of which are crucial for both photosynthesis efficiency and industrial applications. These films have the unique ability to manipulate light at specific wavelengths by concentrating, absorbing, or even scattering certain portions of the light band spectrum. This selective alteration of light quality, particularly within the visible range, can affect the light intensity and spectral composition received by the algae cells. These changes in the light environment influence the photosynthetic machinery and metabolic pathways, leading to adjustments in the production of various cellular components.

3.3.1. Proteins, Lipids, Carbohydrates, and Ash Content. The biomass produced using different plasmonic thin films was biochemically characterized (namely, proteins, lipids, carbohydrates, and ash content) at the end of each trial, and the results are presented in Figure 2.

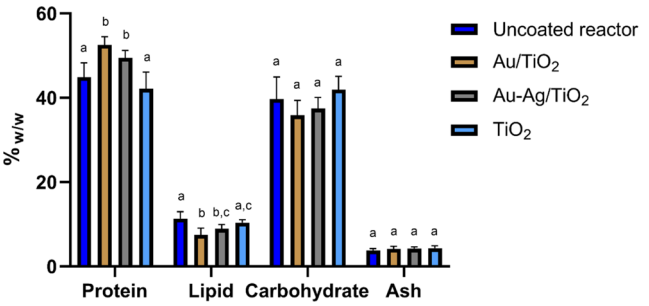


Figure 2. Proximate composition, in percentage of total dry weight, of *C. vulgaris* grown in the 50 mL PBRs using different plasmonic thin film coatings. All data are expressed as mean ± standard deviation from three biological replicates (n = 3). Different letters within the same class of compounds represent significant differences between the values ($p < 0.05$).

Alternative proteins are not only a response to consumer demand but also the way forward for reducing environmental impact and preserving biodiversity. This study was able to achieve a variation in protein content from *C. vulgaris* of between 44.9 ± 3.4 and 52.5 ± 1.9 (% w/w, based on dry mass). Comparing the biomass growth in the different PBR formulations, protein content was 1.2-fold (15% higher) in microalgae grown on Au/TiO_2-coated PBR than the uncoated PBR ($p < 0.05$). Au−Ag/TiO_2-coated PBR also achieved a higher percentage of protein than the uncoated PBR (about 10% higher), with statistically significant differences ($p < 0.05$). However, when comparing both plasmonic PBRs, Au/TiO_2 and Au−Ag/TiO_2, no statistically significant differences were obtained between them ($p > 0.05$). These results suggest that the use of plasmonic NPs as light quality enhancement devices in PBRs can significantly promote protein synthesis in photosynthetic microorganisms. Baidya et al.[30] analyzed the impact of different wavelengths on microalgae growth and found that providing light in the blue band promoted an increase in protein content (about 10%), compared to white light, while the red band negatively affected protein accumulation (about 20% reduction). This result is in line with those obtained in the present study since the use of Au NPs on the glass walls restricts the passage of light to the cells in the red band, resulting in an increase in protein content. Conversely, shifting the LSPR band wavelength to the orange range (using Au−Ag/TiO_2-coated PBR) also induces protein synthesis, but with less impact than at longer wavelengths. This might be explained by the increased incorporation of carbon-14 isotope into protein-bound amino acids under lower

https://doi.org/10.1021/acssuschemeng.4c06367
ACS Sustainable Chem. Eng. 2025, 13, 791−799

wavelengths, which specifically promotes the rate of protein synthesis.[30]

Concerning other fractions of microalgae biomass (Figure 2), lipids and carbohydrates content exhibited variations ranging between 7.5 ± 1.6 and 11.3 ± 1.6 and between 35.8 ± 3.6 and 41.9 ± 3.2 (% w/w, based on dry mass), respectively. These biochemical fractions presented an opposite relation to protein synthesis, manifesting a content decrease in the assays, where protein production was enhanced. In this sense, biomass grown in the plasmonic PBRs showed a 34% (Au/TiO_2) and 21% ($Au–Ag/TiO_2$) reduction in lipids content, respectively, compared to the uncoated PBR ($p < 0.05$). Additionally, there were no statistical differences between the bioreactor coated with only the matrix (TiO_2) and the control condition. The same pattern was observed for the production of carbohydrates, where the plasmonic PBRs showed decreases in their content, whereas the TiO_2-coated PBR showed values similar to those of the control condition. However, no statistical differences were obtained between the various coatings and the control ($p > 0.05$). Lipids and carbohydrates, classified as reserve metabolites, tend to increase their content under stressful situations. In response to adverse conditions, microalgae engage a cellular protection mechanism that becomes activated. In these cases, it is common to have a decrease in protein content (metabolism associated with growth) and an increase in lipids and carbohydrates (reserve metabolism, boosting the production of high-energy compounds). Bearing this in mind, the results suggest that the use of plasmonic thin film coatings has a positive effect on the quality of light reaching microalgae cells. As there was an increase of protein content and a decrease in reserve metabolites in both plasmon-coated PBRs, cells were probably less exposed to unfavorable and stressful situations. A study reported by Estime et al.[31] found that incorporating Ag NPs into a polymer film placed on the outside of the cultivation system, envisaging an enhancement of blue light due to scattering in Ag NPs, did not induce statistically significant differences in both lipids and carbohydrates content. In contrast to the current study, the synthesis of lipids in *C. vulgaris* exhibited a decline under plasmonic NP-influenced conditions, suggesting a connection with the light band to which the microalgae are exposed. Nevertheless, the same authors demonstrated that the plasmonic film with Ag NPs produced a light absorption peak near 440 nm, that is, within the blue region of the spectrum, thereby delineating distinct spectral regions from those obtained in the present work (suppressed light in the orange and red band). Another study conducted by Michael et al.[32] conceptualized a different strategy for improving the quality of light reaching the cells. The authors used filters made of a nanometric coating with layers of metal oxides that are capable of selectively transmitting specific wavelengths (in this case, blue and red) of natural sunlight. The authors observed that the biomass produced in the PBR coated with the blue filter reached a lower lipid and carbohydrate content, compared to the biomass produced by the red filter. These results indicated that the supply of higher wavelengths, such as those in the orange and red ranges, led to lower protein synthesis and a higher accumulation of reserve metabolites, showing trends similar to those obtained in the present study.

3.3.2. Pigments Accumulation. The impact of the different plasmonic thin films on the accumulation of microalgal pigments—chlorophylls *a* and *b* and carotenoids—was also quantified, being the results displayed in Figure 3.

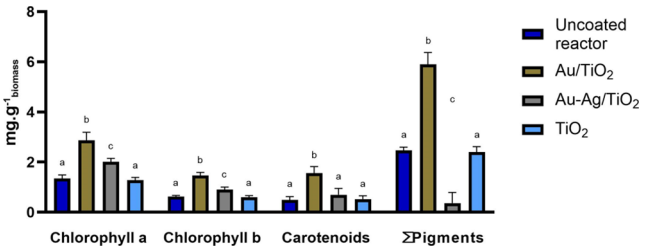


Figure 3. Pigments profile, in $mg{\cdot}g_{biomass}^{-1}$, of *C. vulgaris* grown in 50 mL PBRs using different plasmonic thin film coatings. All data are expressed as mean ± standard deviation from three biological replicates ($n = 3$). Different letters within the same class of pigments represent significant differences between the values ($p < 0.05$).

The primary photosynthetic pigments, chlorophylls *a* and *b*, represent essential compounds that serve not only as additives in pharmaceutical formulations but also in cosmetic products.[7] These pigments act as fundamental agents in the absorption of light energy during photosynthesis. Likewise, carotenoids are a diverse group of pigments that play critical roles in photosynthesis, helping capture light energy, safeguarding cells from excess light, participating in the transfer of energy to chlorophyll molecules, and scavenging free radicals that can cause damage to cells.[33] Light quality significantly influences pigment accumulation.[7] In the present work, comparing the control condition with the different thin films employed for coating the PBRs' glass surfaces, significant variations were observed in pigment accumulation. Particularly, chlorophylls *a* and *b*, as well as carotenoids, displayed ranges from 1.3 ± 0.1 to 2.9 ± 0.3, 0.60 ± 0.07 to 1.5 ± 0.1, and 0.5 ± 0.1 to 1.6 ± 0.3 $mg{\cdot}g_{biomass}^{-1}$, respectively. Significant differences were also observed in the total amount of pigments, with the Au/TiO_2-coated PBR having the highest concentration 5.9 ± 0.5 $mg{\cdot}g_{biomass}^{-1}$, followed by the $Au–Ag/TiO_2$-coated PBR having 3.6 ± 0.4 $mg{\cdot}g_{biomass}^{-1}$. The biomass grown in the Au/TiO_2-coated PBR showed outstanding values, corresponding to 2.1-fold (113% increase) and 2.4-fold (136% increase) in chlorophylls *a* and *b* content, respectively, compared to the uncoated PBR ($p < 0.05$). The PBR with the $Au–Ag/TiO_2$ also showed an increase, about 1.5-fold, in both chlorophyll *a and b*, with statistical differences for the other conditions ($p < 0.05$). The PBR coated only with the TiO_2 matrix obtained concentrations similar to those of the uncoated reactor, with no statistical differences ($p > 0.05$). This clearly suggests that the impact on the chlorophyll profile was exclusively influenced by the presence of the noble metal NPs.

Regarding carotenoids, the same trend was observed, where statistically significant differences were obtained between the uncoated- and NP-coated PBRs ($p < 0.05$). Noteworthy, in the presence of the Au/TiO_2 thin film coating, the concentration of these pigments surpassed the control by 218%, corresponding to a 3.2-fold increase. Additionally, the PBR coated with $Au–Ag/TiO_2$ thin film exhibited a more modest 1.4-fold increment compared to the control. Considering the findings deriving from this analysis, it can be claimed that the LSPR band position and profile, especially the one ascribed to the Au/TiO_2 thin film, considerably enhances the synthesis of all pigments analyzed. The same trend was observed for the shifted LSPR band of $Au–Ag/TiO_2$-coated PBR, although with

https://doi.org/10.1021/acssuschemeng.4c06367
ACS Sustainable Chem. Eng. 2025, 13, 791−799

lower performance compared with the monometallic counterpart system. Therefore, it is important to highlight that the PBRs containing plasmonic thin films revealed outstanding behavior compared to the uncoated PBR (where cultures were exposed to the full visible spectrum through white light).

In a related work, to improve the quality of light supplied to microalgae, Mohsenpour et al.[34] observed increases in the concentrations of chlorophylls *a* and *b* (about 50 and 36%, respectively), as well as carotenoids (about 50%), when microalgae were exposed to red light. These results suggested that the wavelengths associated with this specific range stimulated pigmentation in the biomass. Furthermore, they concluded that there is no linear relationship between biomass production and the pigment profile, indicating that illuminating microalgae with specific wavelengths does not necessarily result in a simultaneous increase in biomass production and pigment accumulation. However, contrasting results were obtained in the present study, since the PBR coated with Au NPs (i.e., with wavelengths restricted in the red-light range) promoted greater pigments accumulation. In another work, mentioned before, Eroglu et al.[28] analyzed the impact of the application of Ag, Au, and Au−Ag NPs in solution on the accumulation of total chlorophylls and carotenoids. The authors found that after 16 days of cultivation, all conditions tested had considerable increases compared to the control. Among the different coatings, they found that the condition with the combined Ag NPs and Au NRs (showing a double absorbance peak at 404 and 642 nm) induced greater accumulation of both classes of pigments analyzed. The increases were approximately 163% for total chlorophylls and 81% for carotenoids. This was sequentially followed by the coatings utilizing Au NRs (single maximum peak of 642 nm) and Ag (single maximum peak of 404 nm), individually.

Another study exploring plasmonic technology in PBRs was conducted by Estime et al.,[35] in which Au NRs (showing a single plasmon absorbance spectrum with a peak of 675 nm) and a mixture of Au NRs and Ag nanospheres (NSs) (showing a double maximum peak of 400 and 675 nm) were incorporated into a polymeric film applied externally on the bottom of the reactor. The authors concluded that both conditions tested resulted in increases in the accumulation of both chlorophylls and carotenoids, although with a lower impact than that observed in the present study.

These results clearly confirm that the application of plasmonic NPs induces a better quality in the microalgal biomass but essentially in the pigment profile. In the present investigation, the Au/TiO_2-coated PBR induced higher pigment concentrations than the other works reported in the literature. In fact, it was initially expected that the bimetallic Au−Ag thin film would generate enhanced plasmonic behavior due to the incorporation of Ag, a behavior theoretically demonstrated in a previous work.[19] Nevertheless, experimentally, it was observed that Au/TiO_2 was more efficient to distribute light wavelengths to the cultures. According to the spectra of Figure 1, the thin film containing Au NPs revealed higher absorbance values, which can explain its enhanced performance compared to Au−Ag NPs, even if the latter is shifted to lower wavelengths. The reason for such behavior is related to the chemical concentration of each individual element (Au and Ag). It seems that bimetallic NPs, with a ratio 1:1, are very stable, though the small excess of Ag that might exist in the thin film is prone to diffuse to the surface and eventually not contribute to the LSPR band. Therefore, the lower extinction efficiency of Au−Ag NPs is probably associated with an overall decrease in noble metal NPs concentration within the thin film. This effect can easily be mitigated by increasing the amount of both noble metals during the production process using the reactive magnetron sputtering, since this technique is very versatile to tailor the film's composition, and hence the noble metal content.

4. CONCLUSIONS

Plasmonic thin films were used to tune electromagnetic wavelengths and the quality of light reaching *C. vulgaris* cultures. The coatings tested had an impact on the light transmittance profile, with changes essentially occurring at higher wavelengths in the visible spectrum. While not impacting biomass production, the application of Au NPs increased the quality of biomass with an increase of 15% for proteins and 218% in the accumulation of total carotenoids. On the other hand, the thin film containing bimetallic Au−Ag NPs also yielded improved results in terms of the quality of biomass, though its impact was less pronounced than that of thin film containing Au NPs. With these beneficial effects, the employed physical vapor deposition technology (reactive magnetron sputtering), recognized as an eco-friendly approach to prepare thin film coatings, has significant potential to be applied in large-scale PBRs for microalgae cultivation, increasing the accumulation of high-value pigments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.4c06367.

Additional experimental details including photographs of the experimental characteristics and setup (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Joel Borges − *Physics Center of Minho and Porto Universities (CF-UM-UP), University of Minho, 4800-058 Guimarães, Portugal; LaPMET−Laboratory of Physics for Materials and Emergent Technologies, University of Minho, 4710-057 Braga, Portugal;* orcid.org/0000-0001-7421-6902; Email: joelborges@fisica.uminho.pt

Authors

Francisco Pereira − *CEB−Centre of Biological Engineering, University of Minho, 4710-057 Braga, Portugal*

António A. Vicente − *CEB−Centre of Biological Engineering, University of Minho, 4710-057 Braga, Portugal; LABBELS − Associate Laboratory, 4710-057 Braga, Portugal;* orcid.org/0000-0003-3593-8878

Filipe Vaz − *Physics Center of Minho and Porto Universities (CF-UM-UP), University of Minho, 4800-058 Guimarães, Portugal; LaPMET−Laboratory of Physics for Materials and Emergent Technologies, University of Minho, 4710-057 Braga, Portugal;* orcid.org/0000-0001-5506-996X

Pedro Geada − *CEB−Centre of Biological Engineering, University of Minho, 4710-057 Braga, Portugal; LABBELS − Associate Laboratory, 4710-057 Braga, Portugal*

Complete contact information is available at: https://pubs.acs.org/10.1021/acssuschemeng.4c06367

Funding

This study was supported by the Portuguese Foundation for Science and Technology (FCT) under the scope of the strategic funding UIDB/04650/2020 and UIDP/04469/2020 unit, with DOI 10.54499/UIDB/04469/2020, and by LABBELS—Associate Laboratory in Biotechnology, Bioengineering and Microelectromechanical Systems, (LA/P/0029/2020). This work was also funded under the scope of the project CO2Plasmon, with FCT reference EXPL/CTM-REF/0750/2021 (10.54499/EXPL/CTM-REF/0750/2021).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Pedro Geada acknowledges FCT for the Junior Research contract obtained under the scope of the Scientific Stimulus Employment with the reference 2022.00930.CEECIND/CP1718/CT0023 (10.54499/2022.00930.CEECIND/CP1718/CT0023). Joel Borges acknowledges FCT for his research contract funding, reference CEECINST/00156/2018/CP1642/CT0001 (10.54499/CEECINST/00156/2018/CP1642/CT0001).

■ REFERENCES

(1) Abreu, A. P.; Morais, R. C.; Teixeira, J. A.; Nunes, J. A comparison between microalgal autotrophic growth and metabolite accumulation with heterotrophic, mixotrophic and photoheterotrophic cultivation modes," May 01,. *Renewable Sustainable Energy Rev.* **2022**, *159*, No. 112247.

(2) Peter, A. P.; Koyande, A. K.; Chew, K. W.; Ho, S.; Chen, W.; Chang, J.; Krishnamoorthy, R.; Banat, F.; Show, P. L. Continuous cultivation of microalgae in photobioreactors as a source of renewable energy: Current status and future challenges. *Renewable Sustainable Energy Rev.* **2022**, *154*, No. 111852.

(3) Dębowski, M.; Zieliński, M.; Kazimierowicz, J.; Kujawska, N.; Talbierz, S. Microalgae cultivation technologies as an opportunity for bioenergetic system development—advantages and limitations. *Sustainability* **2020**, *12*, No. 9980.

(4) Bhushan, S.; Kalra, A.; Simsek, H.; Kumar, G.; Prajapati, S. K. Current trends and prospects in microalgae-based bioenergy production. *J. Environ. Chem. Eng.* **2020**, *8*, No. 104025.

(5) Pruvost, J.; Le Gouic, B.; Lepine, O.; Legrand, J.; Le Borgne, F. Microalgae culture in building-integrated photobioreactors: Biomass production modelling and energetic analysis. *Chem. Eng. J.* **2016**, *284*, 850−861.

(6) Chowdury, K. H.; Nahar, N.; Deb, U. K. The Growth Factors Involved in Microalgae Cultivation for Biofuel Production: A Review. *Comput. Water, Energy, Environ. Eng.* **2020**, *09* (04), 185−215.

(7) Ramanna, L.; Rawat, I.; Bux, F. Light enhancement strategies improve microalgal biomass productivity. *Renewable Sustainable Energy Rev.* **2017**, *80*, 765−773.

(8) Ooms, M. D.; Dinh, C. T.; Sargent, E. H.; Sinton, D. Photon management for augmented photosynthesis. *Nat. Commun.* **2016**, *7*, No. 12699.

(9) Shekh, A.; Sharma, A.; Schenk, P. M.; Kumar, G.; Mudliar, S. Microalgae cultivation: photobioreactors, CO2 utilization, and value-added products of industrial importance. *J. Chem. Technol. Biotechnol.* **2022**, *97*, 1064−1085.

(10) Singh, V.; Mishra, V. A review on the current application of light-emitting diodes for microalgae cultivation and its fiscal analysis. *Crit. Rev. Biotechnol.* **2023**, *43*, 665−679.

(11) Iasimone, F.; Panico, A.; De Felice, V.; Fantasma, F.; Iorizzi, M.; Pirozzi, F. Effect of light intensity and nutrients supply on microalgae cultivated in urban wastewater: Biomass production, lipids accumulation and settleability characteristics. *J. Environ. Manage.* **2018**, *223*, 1078−1085.

(12) Baer, S.; Heining, M.; Schwerna, P.; Buchholz, R.; Hübner, H. Optimization of spectral light quality for growth and product formation in different microalgae using a continuous photobioreactor. *Algal Res.* **2016**, *14*, 109−115.

(13) Ra, C. H.; Sirisuk, P.; Jung, J. H.; Jeong, G. T.; Kim, S. K. Effects of light-emitting diode (LED) with a mixture of wavelengths on the growth and lipid content of microalgae. *Bioprocess Biosyst. Eng.* **2018**, *41* (4), 457−465.

(14) Langer, J.; Aberasturi, D. J.; Aizpurua, J.; Alvarez-Puebla, R. A.; Auguié, B.; Baumberg, J. J.; Bazan, G. C.; Bell, S. E. J.; Boisen, A.; Brolo, A. G.; Choo, J.; Cialla-May, D.; Deckert, V.; Fabris, L.; Faulds, K.; Abajo, F. J. G.; Goodacre, R.; Graham, D.; Haes, A. J.; Haynes, C. L.; Huck, C.; Itoh, T.; Käll, M.; Kneipp, J.; Kotov, N. A.; Kuang, H.; Ru, E. C.; Lee, H. K.; Li, J.; Ling, X. Y.; Maier, S. A.; Mayerhöfer, T.; Moskovits, M.; Murakoshi, K.; Nam, J.; Nie, S.; Ozaki, Y.; Santos, I. P.; Juste, J. P.; Popp, J.; Pucci, A.; Reich, S.; Ren, B.; Schatz, G. C.; Shegai, T.; Schlücker, S.; Tay, L.; Thomas, K. G.; Tian, Z.; Duyne, R. P. V.; Dinh, T. V.; Wang, Y.; Willets, K. A.; Xu, C.; Xu, H.; Xu, Y.; Yamamoto, Y. S.; Zhao, B.; Marzán, L. M. L. Present and Future of Surface-Enhanced Raman Scattering. *ACS Nano* **2020**, *14*, 28−117.

(15) Wang, L.; Kafshgari, M. H.; Meunier, M. Optical Properties and Applications of Plasmonic-Metal Nanoparticles. *Adv. Funct. Mater.* **2020**, *30*, No. 2005400.

(16) Kristensen, A.; Yang, J.; Bozhevolnyi, S.; Link, S.; Nordlander, P.; Halas, N. J.; Mortensen, N. A. Plasmonic colour generation. *Nat. Rev. Mater.* **2016**, *2*, No. 16088.

(17) Kumar, A.; Choudhary, P.; Kumar, A.; Camargo, P. H. C.; Krishnan, V. Recent Advances in Plasmonic Photocatalysis Based on TiO2 and Noble Metal Nanoparticles for Energy Conversion, Environmental Remediation, and Organic Synthesis. *Small* **2022**, *18*, No. 2101638.

(18) Rodrigues, M. S.; Borges, J.; Lopes, C.; Pereira, R. M. S.; Vasilevskiy, M. I.; Vaz, F. Gas sensors based on localized surface plasmon resonances: Synthesis of oxide films with embedded metal nanoparticles, theory and simulation, and sensitivity enhancement strategies. *Appl. Sci.* **2021**, *11*, No. 5388.

(19) Meira, D. I.; Rodrigues, M. S.; Borges, J.; Vaz, F. Enhancing the Extinction Efficiency and Plasmonic Response of Bimetallic Nanoparticles of Au-Ag in Robust Thin Film Sensing Platforms. *Sensors* **2023**, *23* (23), No. 9618.

(20) Ooms, M. D.; Bajin, L.; Sinton, D. Culturing photosynthetic bacteria through surface plasmon resonance. *Appl. Phys. Lett.* **2012**, *101* (25), No. 253701.

(21) Torkamani, S.; Wani, S. N.; Tang, Y. J.; Sureshkumar, R. Plasmon-enhanced microalgal growth in miniphotobioreactors. *Appl. Phys. Lett.* **2010**, *97*, No. 043703.

(22) An, X.; Naowarojna, N.; Liu, P.; Reinhard, B. M. Hybrid Plasmonic Photoreactors as Visible Light-Mediated Bactericides. *ACS Appl. Mater. Interfaces* **2020**, *12* (1), 106−116.

(23) Fernandes, B. D.; Dragone, G. M.; Teixeira, J. A.; Vicente, A. A. Light regime characterization in an airlift photobioreactor for production of microalgae with high starch content. *Appl. Biochem. Biotechnol.* **2010**, *161* (1−8), 218−226.

(24) Naderi, G.; Tade, M. O.; Znad, H. Modified Photobioreactor for Biofixation of Carbon Dioxide by Chlorella vulgaris at Different Light Intensities. *Chem. Eng. Technol.* **2015**, *38* (8), 1371−1379.

(25) Sousa, V.; Loureiro, L.; Carvalho, G.; Pereira, R. N. Extraction of biomolecules from Coelastrella sp. LRF1 biomass using Ohmic Heating technology. *Innovative Food Sci. Emerging Technol.* **2022**, *80*, No. 103059.

(26) Geada, P.; Francisco, D.; Pereira, F.; Maciel, F.; Madureira, L.; Barros, A.; Silva, J. L.; Vicente, A. A.; Teixeira, J. A. Multivariable optimization process of heterotrophic growth of Chlorella vulgaris. *Food Bioprod. Process.* **2023**, *138*, 1−13.

(27) Pedron, F.; Grifoni, M.; Barbafieri, M.; Petruzzelli, G.; Franchi, E.; Samà, C.; Gila, L.; Zanardi, S.; Palmery, S.; Proto, A.; Vocciante, M. F. New light on phytoremediation: The use of luminescent solar concentrators. *Appl. Sci.* **2021**, *11* (4), No. 1923.

(28) Eroglu, E.; Eggers, P. K.; Winslade, M.; Smith, S. M.; Raston, C. L. Enhanced accumulation of microalgal pigments using metal nanoparticle solutions as light filtering devices. *Green Chem.* **2013**, *15* (11), 3155−3159.
(29) Ooms, M. D.; Jeyaram, Y.; Sinton, D. Wavelength-selective plasmonics for enhanced cultivation of microalgae. *Appl. Phys. Lett.* **2015**, *106*, No. 063902.
(30) Baidya, A.; Akter, T.; Islam, R.; Shah, A. K. M. A.; Hossain, A.; Salam, M. A.; Paul, S. I. Effect of different wavelengths of LED light on the growth, chlorophyll, β-carotene content and proximate composition of Chlorella ellipsoidea. *Heliyon* **2021**, *7* (12), No. e08525.
(31) Estime, B.; Ren, D.; Sureshkumar, R. Effects of plasmonic film filters on microalgal growth and biomass composition. *Algal Res.* **2015**, *11*, 85−89.
(32) Michael, C.; del Ninno, M.; Gross, M.; Wen, Z. Use of wavelength-selective optical light filters for enhanced microalgal growth in different algal cultivation systems. *Bioresour. Technol.* **2015**, *179*, 473−482.
(33) Begum, H.; Yusoff, F. M. D.; Banerjee, S.; Khatoon, H.; Shariff, M. Availability and Utilization of Pigments from Microalgae. *Crit. Rev. Food Sci. Nutr.* **2016**, *56* (13), 2209−2222.
(34) Mohsenpour, S. F.; Richards, B.; Willoughby, N. Spectral conversion of light for enhanced microalgae growth rates and photosynthetic pigment production. *Bioresour. Technol.* **2012**, *125*, 75−81.
(35) Estime, B.; Ren, D.; Sureshkumar, R. Tailored Fabrication of Plasmonic Film Light Filters for Enhanced Microalgal Growth and Biomass Composition. *Nanomaterials* **2024**, *14* (1), No. 44.

https://doi.org/10.1021/acssuschemeng.4c06367
ACS Sustainable Chem. Eng. 2025, 13, 791−799