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A Review of Insights into Algae as a Sustainable Bio-based Photocatalyst for Environmental Remediation

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Abstract

Algae have recently emerged as a promising photocatalyst material due to their abundancy, low cost, and environmentally friendly nature. This review summarizes recent progress on utilizing algae as bio-based photocatalysts. Eutrophication and abundance of algae which make it an ideal candidate as a sustainable photocatalyst source, have been discussed. Recent work on synthesis methods such as hydrothermal treatment, calcination, and templating to produce photocatalytically active algae nanoparticles (NPs) has been reviewed. Photocatalytic activity of algae-based materials have been studied such as wastewater treatment, dye removal, and heavy metal remediation. Finally, strategies to further enhance algae's photocatalytic performance, including coating and doping with metals, coupling with graphene, and heterogeneous integration are highlighted here. To wrap up, this review underscores the exciting potential of algae as a sustainable and effective next-generation photocatalytic material.

Keywords: algae; biosynthesis; photocatalyst; algae nanoparticles; phycosynthesis

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INTRODUCTION

The unprecedented escalation of algal blooms, catalyzed by unfettered nutrient enrichment of water bodies, elicits global ecological concerns (Patricia et al., 2017; Zhang et al., 2022). However, the burgeoning algal biomass can prospectively be harnessed as a sustainable feedstock for synthesizing nanocatalysts to mitigate environmental impacts while propelling green chemical synthesis pathways.

The major culprit precipitating algal overpopulation is eutrophication, stimulated by excessive influx of nutrients like nitrates and phosphates due to indiscriminate discharge of agricultural runoffs and domestic sewage into water systems as illustrated in **Figure 1** (Devlin & Brodie, 2023). This enrichment stimulates unchecked photosynthesis, creating algal blooms whose eventual death and degradation severely destabilizes aquatic ecosystems and tremendous degradation of water quality (Wurtsbaugh et al., 2019; Ramadhani & Said, 2023). However, the copious microalgal biomass accrued before the inevitable population crash represents an abundant carbon-neutral feedstock that can be strategically tapped as renewable photoreactors for energy transduction (Sundaram et al., 2023). This population also presents opportunities to utilize the rapidly proliferating algae as a sustainable source of photocatalysts. The high availability and renewable nature of eutrophic algae make it ideal as an inexpensive, green photocatalyst feedstock (Adeniyi et al., 2018; Dîrja et al., 2011).

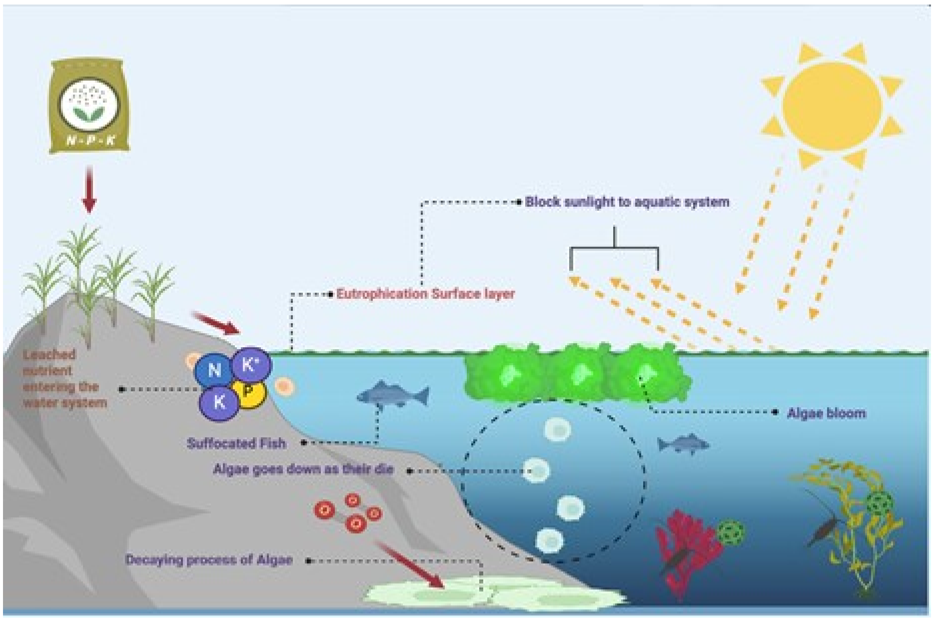

Figure 1. Eutrophication Mechanism and Its Effect on the Aquatic Ecosystem (The figure was fully drawn by BioRender).

With over 100,000 known species, algae represent one of the most diverse and abundant organisms on Earth (Sherwood, 2016). They occur ubiquitously in marine and freshwater systems (Petersen et al., 2021). The rapid, uncontrolled proliferation of algae due to eutrophication leads to algal blooms that can be exploited as a rich source for harvesting and synthesizing photocatalysts in a renewable manner (Li et al., 2022). This abundance and renewability confer significant advantages over conventional photocatalysts derived from non-renewable sources (Zhu & Wang, 2017). Their ecological success stems from a highly efficient photosynthetic apparatus which converts solar irradiance and CO_2 into bioenergy. Thus, the massive productivity during algal blooms offers a unique opportunity to sustainably derive value from this photosynthesis-derived biochemical reactor by integrating it with inorganic nanomaterials to potentially realize augmented photocatalytic hybrids.

The photosynthetic organelles in algae called chloroplasts, along with other intrinsically embedded redox cofactors, provide multiple targets for structural augmentation and nanocompositing to potentially elicit enhanced photocatalysis. Common approaches include biomimetic mineralization, genetic and metabolic modulation, and hierarchical integration with micro/nanostructures to render the base algal scaffold more proficient in harvesting solar photons and channelling the energy toward target catalytic reactions. Algae possess several intrinsic characteristics that make them well-suited as photocatalysts. Photosynthetic algae contain light-harvesting pigments like chlorophyll and carotenoids, which act as photosensitizers to generate reactive oxygen species (Kato & Shinomura, 2020; Larkum & Weyrauch, 1977). Algae cell walls also contain polysaccharides and functional groups that facilitate pollutant adsorption (Vinayak et al., 2021). Furthermore, the nanoscale features of algae cell components lead to a high specific surface area beneficial for catalysis (X. Chen et al., 2017; Kibsgaard et al., 2012). These inherent traits, combined with their renewability and abundance, emphasize algae's tremendous potential as bio-based photocatalysts (Serrà, Pip, et al., 2020; Tu et al., 2021; X. Wang et al., 2018).

In this review, we survey recent biotechnological endeavours focused explicitly on recruiting the endogenous photosynthetic and redox apparatus within algal scaffolds as viable photocatalytic nanofactories via structural and compositional modifications. Specifically, we highlight advances in tailoring complex algae-inorganic hybrid nanoarchitectures with spatially-optimized topologies and defect engineering strategies which can judiciously couple the photo-excited state and catalytic active sites to augment solar energy transduction efficiencies.

METHOD

An investigative review of the literature was conducted to compile relevant studies published over the past decade (2010-2024) on exploring and harnessing the photocatalytic potential of algae. Several scholarly databases involving PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar were mined using targeted keyword combinations such as “phycosynthesis for photocatalytic activity”, “algae bio-photocatalyst”, "algae photocatalyst", "algae NPs photocatalysis", “microalgae heterojunction”, “algae genetic engineering photocatalysis”, and “algae metabolically engineered photocatalysis”. Additional filters were applied to only retrieve English language articles published in peer-reviewed academic journals.

The search results were screened in two phases - titles and abstracts and then assessed to identify potentially relevant papers. Subsequently, the results were analyzed in their entirety through full-texts to collate those focused explicitly on developing algal photocatalysts and deriving mechanistic insights on structure-function optimization. Research articles that met the inclusion criteria were included in the analytical review framework constructed as shown by **Figure 2** to coherently assess advancements and challenges.

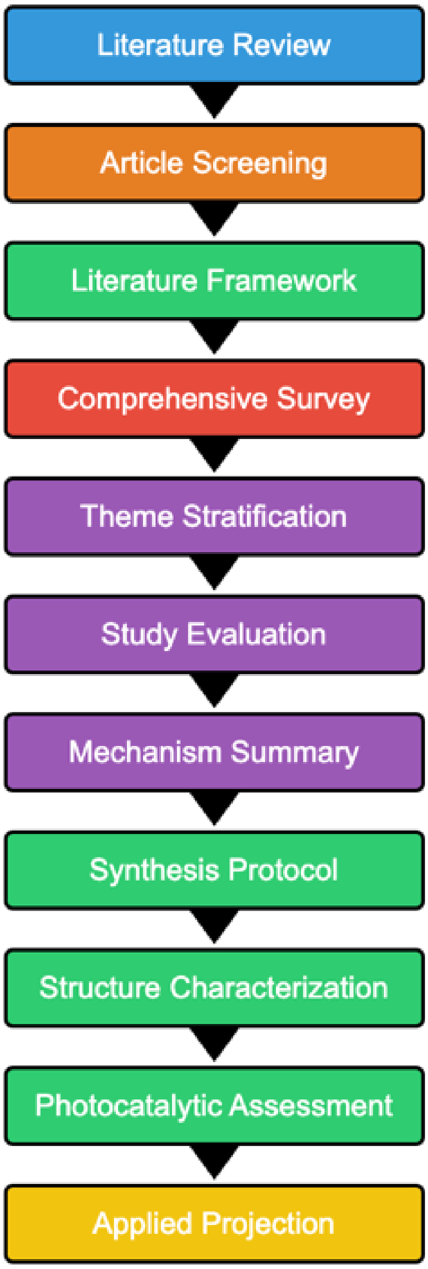

Figure 2. Literature review framework used in this study

The vast literature landscape was stratified into key themes centered on fabrication strategies for algae-based photocatalysts encompassing bio-inspired hierarchical nano-assembly techniques and green synthesis method. Each study under these categories was evaluated in-depth to chart emerging synthesis protocols, characterize resultant nano/microstructures, appraise photocatalytic efficiency for different reactions, and weigh projected real-world viability. Additionally, latest understandings clarifying mechanisms underlying enhancements in photocatalytic activity due to structurally integrating algae with inorganic nanomaterials were distilled to inform future rational design strategies. By comprehensively surveying and filtering the vast literature in this sequential manner combining quantitative and qualitative appraisal strategies, this review constructed a robust foundation to realistically assess the state-of-art and project future milestones for establishing algae as a disruptive photocatalytic feedstock bridging sustainability science and environmental nanotechnology domains.

RESULTS AND DISCUSSION

Photocatalysis Overview

Photocatalysis has emerged as a promising approach for environmental remediation especially in scope of wastewater treatment (Bhanderi et al., 2024; Fatimah et al., 2015). The basic principle relies on using photocatalysts to absorb light and generate electron-hole pairs, which then drive chemical reactions (Yang et al., 2022). Over the past few decades, extensive research efforts have focused on developing efficient photocatalytic systems using semiconductor materials (Samia et al., 2024).

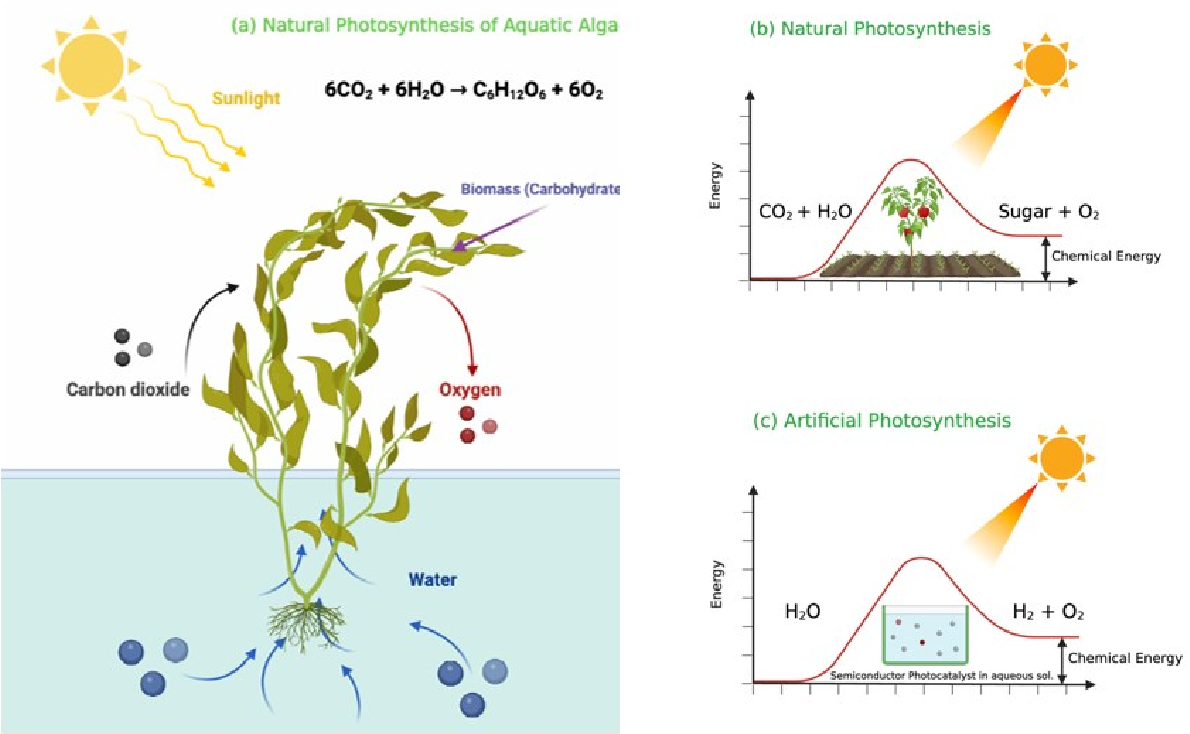

Figure 3. Schematic Representation of **(a)** Natural Photosynthesis Process of Aquatic Algae (*Macrocystis pyrifera*), **(b)** Natural Photosynthesis in general, and **(c)** Artificial Photosynthesis mechanism (the sub-figure of (b) and (c) was adopted from Kudo & Miseki (2008)).

In artificial photosynthesis, aquatic algae and cyanobacteria perform photocatalytic water splitting to convert solar energy to chemical energy as shown in **Figure 3(c)** (Machín et al., 2023; Shevela et al., 2019). They use photosystem II to oxidize water and release oxygen, while photosystem I reduces electron carriers to generate reducing equivalents (Lubitz et al., 2019). Inspired by these natural systems, artificial photocatalytic systems aim to replicate similar pathways for solar fuel production and wastewater treatment (pollutant degradation) (Hassaan et al., 2023).

Photocatalytic water treatment utilizes semiconductor catalysts which can generate reactive chemical species when irradiated with light, as illustrated in **Figure 4**. Specifically, when a semiconductor is illuminated with photons carrying energy greater than its band gap, electrons can be promoted from the valence band to the conduction band, thus creating electron-hole pairs. These charge carriers may then migrate to the catalyst surface where they drive redox reactions with adsorbed species. For instance, photo-generated holes can react with chemisorbed water or hydroxide to produce reactive oxygen species like hydroxyl radicals. Meanwhile, excited electrons can reduce oxygen to produce superoxide radicals. Such powerful oxidants and reductants enable the degradation of organic pollutants and water contaminants when present as aqueous solutions. Indeed, hydroxyl radicals generated on irradiated catalyst surfaces have proven highly effective for the photocatalytic treatment of wastewater streams containing recalcitrant organics.

Among such degradation reactions, hydroxyl radicals have been well-established as effective at treating organic compounds in aqueous solutions. The hydroxyl radicals likely form from reactions involving photo-generated holes and adsorbed hydroxides or water molecules. Photo-generated electrons may likewise reduce oxygen molecules to reactive oxygen species. This semiconductor-catalyzed production of potent oxidizing and reducing agents provides a pathway to aqueous contaminant degradation.

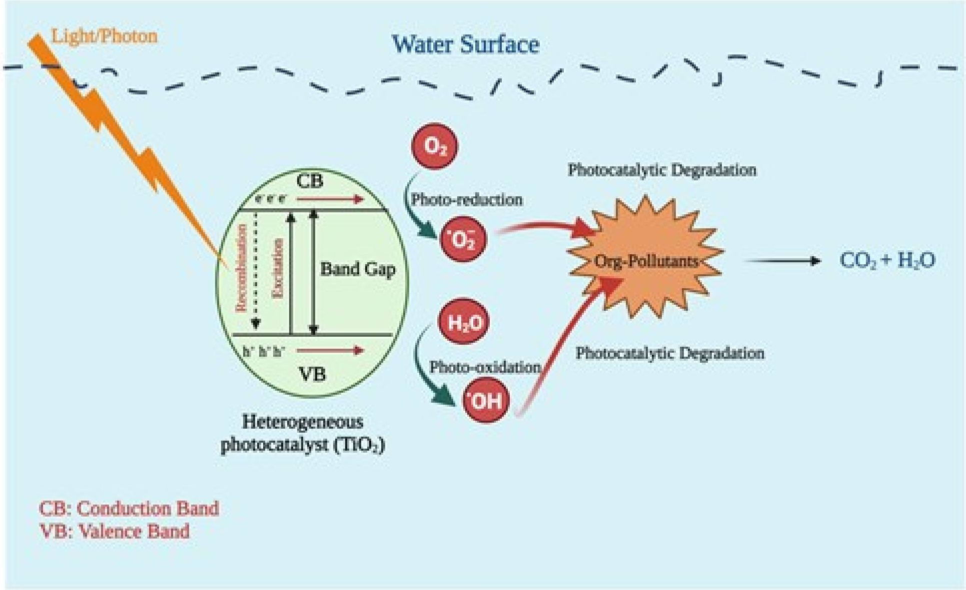

Figure 4. Photodegradation organic compounds in water by heterogeneous photocatalysis scheme (The figure was fully drawn by BioRender).

Materials like TiO_2, ZnO, CdS, and WO_3 have been extensively explored for organic decomposition and water disinfection purposes under UV or visible light illumination (Gao et al., 2017). While laboratory studies indicate high efficiencies, real-world applications still face limitations like rapid electron-hole recombination, insufficient visible light utilization, and catalyst recovery issues (Wu et al., 2023). Recent work has investigated sustainable photocatalyst synthesis using waste materials (D. Bristow et al., 2024). Biomass like cellulose and chitin can template and assemble semiconductor nanostructures for photocatalysis (Lizundia et al., 2021). Low-cost photocatalysts synthesized from agricultural residues and industrial wastes using green chemistry routes have shown promising organic degradation capacity (Al Harby et al., 2024).

Photocatalysis innovations through bioinspired materials like algae and interfaces could enable sustainable remediation technologies for both environmental and economic applications. However, significant advancements in efficiency, selectivity, and stability are still required under real-world operating conditions. Further research should emphasize translating bench-scale proofs-of-concept to pre-commercial pilot demonstrations in order to catalyze widespread adoption and impact.

Phycosynthesis: Recent Work and Trend on Algae as Bio-Photocatalyst

Several recent studies have directly demonstrated the photocatalytic activity of modified algae. Red, green, and brown algae species have shown capability for degrading organic pollutants and microbes under solar and UV irradiation. Researchers found that cell wall polysaccharides and alginates play a key role in photocatalysis. Chlorophyll pigments photosensitize to produce reactive oxygen species. However, the photocatalytic performance of pure algae remains modest or even nothing. This has motivated investigations into structural modifications of algae using synthetic methods to enhance their photocatalytic potency. Current work has focused on phycosynthesis – synthesizing algae-based photocatalyst NPs using green synthesis methods. This produces modified algae with higher surface area, porosity, and improved charge separation. Common synthetic strategies include integrating algae with graphene, coating algae with TiO_2 layers, and doping algae with metal nanoparticles. The optimized algae catalysts demonstrate significantly enhanced performance for organics degradation, microbe disinfection, and heavy metal removal. Photocatalytic algae NPs are rapidly emerging as next-generation catalysts that are abundantly available, inherently sustainable, and highly effective.

Algae have proven to be highly effective biofactories for the green and sustainable synthesis of metal nanoparticles, leveraging the biomolecules within specific algal species to mediate nanoparticle fabrication. **Table 1** compiles recent studies demonstrating the diversity of algae genera explored as reducing and capping agents for phycosynthesis of metallic nanocatalysts tailored toward photocatalytic reactions.

Table 1. Species of Algae for Phycosynthesis and Photocatalytic Applications of the Synthesized Nanoparticles

Species of Algae	NPs synthesized and produced	Size of NPs (nm)	Shape of NPs	Applications	Ref.
Chlorella vulgaris	Pd	2-15	Spherical	Catalysis	(Eroglu et al., 2012)
		15	Spherical with good monodispersity	NA	(Arsiya et al., 2017)
Caulerpa racemosa	Ag	Approx. to 25	Distorted spherical	Catalytic degradation of MB	(Edison et al., 2016)
Turbinaria conoides and *Sargassum tenerrimum*	Au	27-35	Nearly spherical	Catalysts for the reduction of aromatic nitro compounds and organic dye molecules	(Ramakrishna et al., 2016)
Chlorella pyrenoidosa	Ag	2-15	Crystalline	Photocatalytic degradation of MB dye	(Aziz et al., 2015)
Hypnea musciformis	Ag	2-55.8	Well-separated spherical	Photocatalytic degradation of methyl orange dye	(Ganapathy Selvam & Sivakumar, 2015)
Sargassum vulgare	Zn	50-150	Spherical	Degradation of methylene blue dye under UV light irradiation	(Karkhane et al., 2020)
Dunaliella tertiolecta and *C. vulgaris*	ZnO	NR	NR	Photocatalyst to hydrocarbon removal from oily water	(Salehi et al., 2019)

Species of Algae	NPs synthesized and produced	Size of NPs (nm)	Shape of NPs	Applications	Ref.
microalgae *Chlorella*	ZnO	20 ± 2.2	Spherical, hexagonal	Photocatalytic activity of DBT photodegradation (organosulfur pollutant)	(Khalafi et al., 2019)
Sargassum myriocystum	Ag	20 ± 2.2	Well dispersed hexagonal	Photocatalytic activity of methylene blue (MB) degradation	(Balaraman et al., 2020)
Ulva lactuca	Ag	48.59	Spherical	Photocatalytic degradation of methyl orange dye	(Kumar et al., 2013)
Chlamydomonas reinhardtii	CdS	Approx. to 5	Spherical	Photocatalytic activity of degradation of methylene blue dye under UV light	(Rao & Pennathur, 2017)
Algae (Chitosan nanofiber)	Algae-TiO_2/Ag	2.88	Spherical	Photocatalytic activity for Cr(VI) removal under visible light	(L. Wang et al., 2017)
Scendesmus sp	Scendesmus/Fe_3O_4/TiO_2	NR	Octagonal	Novel bio-magnetic photocatalyst for degration of Red195 dye under ultrasonic/ UVA irradiation	(Zamani et al., 2023)
Sargassum coreanum	Ag	19	Distorted spherical shape	Catalytic degradation of methylene blue	(Somasundaram et al., 2021)
Padina gymnospora	CdO-ZnO (SCZ)	20-50	Distorted hexagonal	Photocatalytic degradation activity of Reactive Blue 198 dye under the UV light, visible light and natural sunlight irradiation	(Rajaboopathi & Thambidurai, 2017)
Dictyosphaerium sp.	$^{a}BiVO_4$	NR	NR	Photocatalytic degradation of sulfadiazine (SD) and sulfamethazine (SM2) mixtures	(Liu et al., 2022)
Ulva lactuca	Ag	Approx. to 24	Spherical	Antibacterial activity	(Gurusamy et al., 2019)
Chlamydomonas reinhardtii	ZnO	40	Spherical	Photocatalytic degradation activity of methyl orange dye	(Rao & Gautam, 2016)

NA: Not Available ; NR: Not Reported ; NPs: Nanoparticles ; $^{a}BiVO_4$: The Bismuth vanadate is not synthesized as nanoparticles.

As highlighted in **Table 1**, nanoparticles of silver (Ag), gold (Au), zinc (Zn), titanium dioxide (TiO_2) and metal sulfides like cadmium sulfide (CdS) have been preferentially synthesized using algal extracts or biomass across genera spanning *Chlorella*, *Sargassum*, *Ulva*, *Dunaliella*, *Scendesmus* and others. Key physicochemical properties including nanoparticle morphology, dimensions and crystallinity have been characterized and tabulated. Notably, tiny nano-dimensions under 50 nm are commonly achieved using algal biofactories as shown by **Figure 5**, conferring the high surface area to volume ratios desirable for photocatalytic activity. Spherical morphologies facilitating light absorption prove popular, although hexagonal and octagonal nanostructures have also been biosynthesized in few cases.

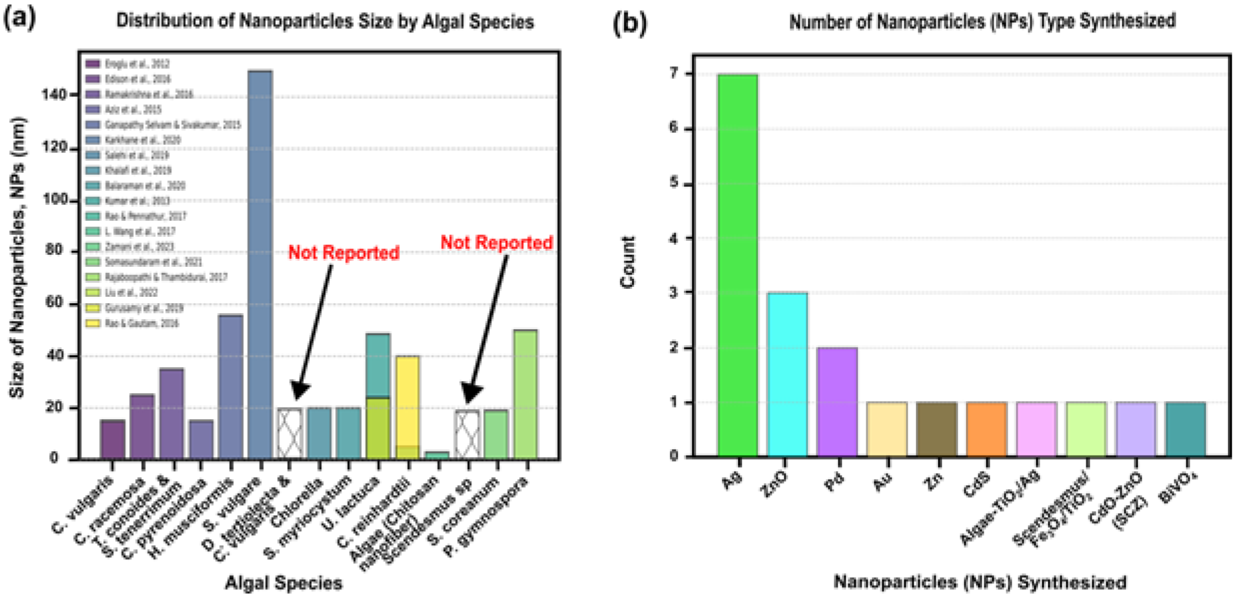

Figure 5. Nanoparticles distribution by algal species

More importantly, **Table 1** documents the diverse photocatalytic applications already investigated using these algal-mediated metallic, metal oxide and semiconductor nanosystems, ranging from organic contaminant degradation, water purification, dye discoloration to wastewater treatment under UV, visible or sunlight exposure. Target pollutants degraded include common water/air pollutants like sulfur organics, crude oil residues, methylene blue, methyl orange and reactive dyes. Such photocatalytic efficacy highlights the versatility of algal nanostructures.

However, most studies are preliminary demonstrations with extensive optimization essential for practical viability. Only few reports have tried to enhance photocatalytic performance via doping, compositing or genetically modifying the base algal biomass. The same trend was also observed for the direct modification of algae cell structured for producing novel bio-photocatalyst material which is reportedly rare. Considerably more interdisciplinary efforts encompassing materials science, biology and synthetic chemistry are imperative to translate the exceptional photocatalyst synthesis potential of algal nano-bioreactors, as captured in **Table 1**, into market-relevant and industrial solutions.

The green microalgae *Chlorella vulgaris* has been widely exploited for efficient biosynthesis of metallic nanoparticles as evidenced in **Table 1**. The prolific synthesis of fairly spherical and crystalline silver nanoparticles around 15 nm mediated by *C. vulgaris* extracts is facilitated by specific biomolecules including proteins, pigments and polysaccharides (Aziz et al., 2015). It is postulated that the algal phytochemicals serve dual functions - the reduction of silver ions is mainly performed by enzymes and by phenolics/flavonoids abundant within *C. vulgaris*, while proteins and saccharides concurrently stabilize the nascent nanoparticles as shown in **Figure 6**. The exact proteins involved however require further isolation and characterization. Critically, the photocatalytic activity for the degradation of methylene blue dye under visible light irradiation arises from synergism between the surface plasmon resonance of Ag NPs and the photosensitizing pigments innately present in the algal extracts.

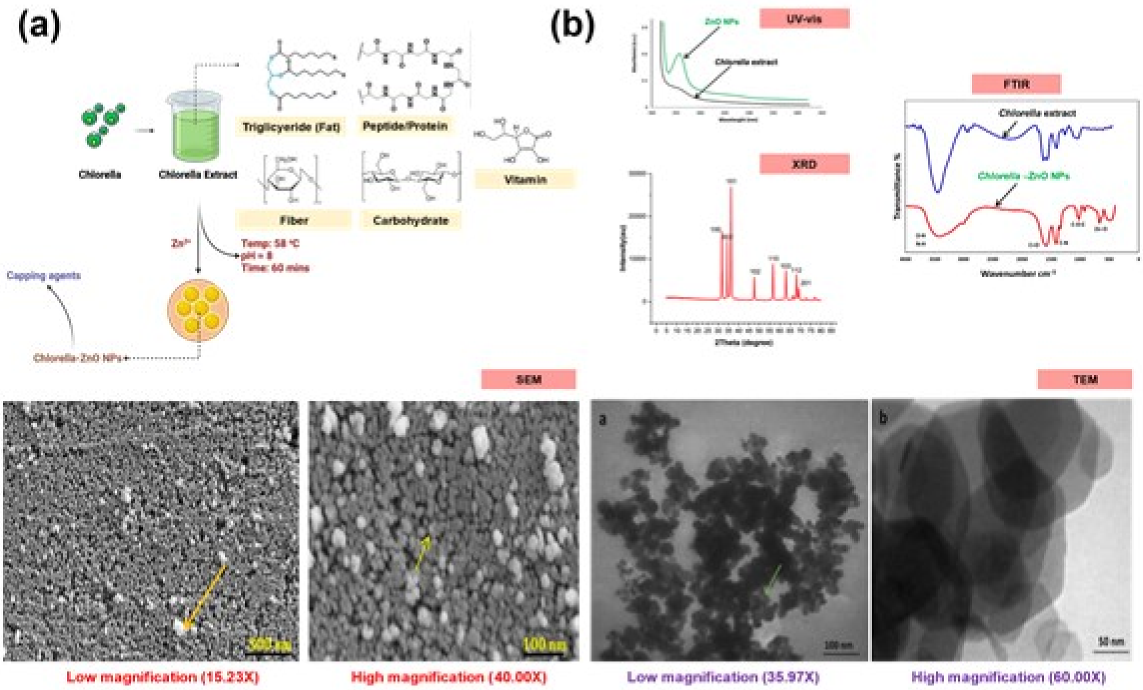

Figure 6. The schematic representation of **(a)** The biosynthesis procedure of utilization of *Chlorella* extract with ZnO to produce *Chlorella*-ZnO NPs photocatalyst material and **(b)** Characterization of biosynthesized ZnO NPs with *Chlorella* extract including the UV-vis spectra, XRD analysis, FTIR analysis, SEM and TEM observations at high and low magnification value (adopted and modified from Khalafi et al. (2019) is licensed under CC BY 4.0).

Sargassum species are also emerging as attractive biogenesists for metallic nanoparticles as photocatalysts from **Table 1** based on the unique polysaccharide-rich matrix and porosity characteristics. For instance, the rapid extracellular synthesis of fairly spherical 19-21 nm silver nanoparticles using *Sargassum myriocystum* (Balaraman et al., 2020) is mediated specifically by sulfate-containing polysaccharides called fucoidans. The sulfated polysaccharides serve as potent reductants to convert silver ions coupled to electrostatic stabilization of the nascent zerrovalent Ag nanoparticles. Concurrently, proteins likely provide additional capping functionality. The fucoidan-capped Ag nanosystems displayed excellent photocatalytic degradation of dyes under sunlight, attributable to synergism between the intrinsic fucoidan sensitizers and plasmonic nanosilver.

Ulva lactuca seaweed has also shown promising metal nanoparticle synthesis capabilities as evident from **Table 1**. The green production of fairly spherical silver nanoparticles around 48.59 nm leverages the redox-active components innately present within aqueous *Ulva* extracts (Kumar et al., 2013). Specifically, the protein components enable the reductive fabrication of Ag atoms from silver nitrate solution. Concurrently, stabilization is imparted by anionic polysaccharides likeUlvan which electrostatically bind to cationic facets on the Ag NPs surface. This enables controlled crystallization resulting in largely spherical particles. Significantly, photocatalytic degradation of methyl orange dye is postulated to occur synergistically through the light sensitization effects of Ulvan and other intrinsic *Ulva* pigments coupled to the localized surface plasmon resonance of biogenic *Ulva*-silver nanocomposites.

Microalgae *Chlamydomonas reinhardtii* has also been genetically and functionally adapted for in-vivo biosynthesis of photocatalytic metal sulfide nanoparticles as outlined in **Table 1**. Expressing a single biosynthetic gene for plant phytochelatin synthase in *C. reinhardtii* induces the algal cells to internally synthesize discrete cadmium sulfide nanoclusters with excellent sphericity (Rao & Pennathur, 2017). Specifically, the phytochelatin peptides produced encapsulate intracellular cadmium and mediate sulfidation to template 5 nm CdS nanodots within genetically transformed algal cells. The internalized nanoparticles can be extracted without cell disruption. Photocatalytic degradation of methylene blue dye is enabled by broadly size-tunable CdS nanosystems achievable simply by modulating expression levels of transgenic *Chlamydomonas*. This underscores the power of algal bioengineering for sustainable in-vivo nano-photocatalyst fabrication.

Table 1 documents the rich promise of diverse algae genera for rapid and sustainable biogenic synthesis of tailored metallic, metal oxide and semiconductor photocatalytic nanoparticulates. It also captures early successes of utilizing such algal nano-biofactories toward photocatalysis reactions under visible and UV light for environmental remediation and antibacterial applications. Finally, it makes a compelling case highlighting the essential need for further advances in understanding, optimizing and applying algal photocatalytic nanosystems to realize their immense potential for sustainable catalysis-driven technologies.

While early successes have been achieved, most studies remain at proof-of-concept levels requiring further optimization. Nonetheless, the rich spectrum of algal biodiversity that can be recruited for tailored nanoparticle synthesis highlights the immense untapped potential of microalgal nanofertilories toward sustainable photocatalyst development.

Green Synthesis Method

Algae have proven to be versatile bio-factories amenable to various green nanofabrication methods that leverage their intrinsic biomolecules for the template-guided synthesis of nanostructured photocatalysts. Such biosynthetic approaches mitigate the need for toxic chemicals, extreme temperatures or pressures, thereby providing benign and energy-efficient photocatalyst production pathways with minimal environmental impact.

Specifically, algal scaffolds can recruit endogenous proteins, pigments, carbohydrates and lipids as shown by **Figure 7** innately embedded within their cell walls or metabolites to direct the fabrication and assembly of nanocatalytic components in a controlled manner. Common green approaches implemented are solvothermal/hydrothermal bio-mineralization and bio-reduction which typically use aqueous algal extracts as stabilizing agents to produce metal/metal oxide nanoparticles. Additionally, genetic and metabolic engineering of live algal cells have enabled in-situ biosynthesis of catalytic nanomaterials by modulating biosynthesis pathways.

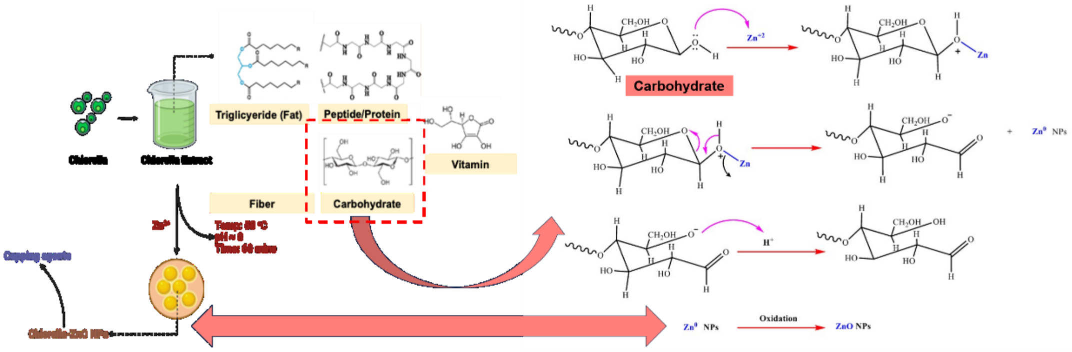

Figure 7. The Plausible mechanism of carbohydrate as bioreducing agent derived from *Chlorella* for biosynthesis of *Chlorella*- ZnO NPs (adopted and modified from Khalafi et al. (2019) is licensed under CC BY 4.0)

Table 2. Algae-based photocatalyst preparation methods, properties, and applications

Algal Species	Preparation Method	NPs synthesized	Reduction of band gap energy	Surface Area (m^2/g)	Applications	Ref.
Chlorella pyrenoidosa	activation/carbonization process	Synthesized as activated charcoal	5.6 - 2.6 eV	272	Photocatalytic activity of Rhodamine B (RhB) dye degradation under UV and visible radiation	(Figueiredo et al., 2020)

Algal Species	Preparation Method	NPs synthesized	Reduction of band gap energy	Surface Area (m^2/g)	Applications	Ref.
Tetradesmus obliquus	bionic dehydrating method	bio-TiO_2	3.24 -3.10 eV	NA	Phenol degradation	(Guo et al., 2023)
Scendesmus sp	sol–gel method	Scendesmus /Fe_3O_4/TiO_2	NR	NR	Novel bio-magnetic photocatalyst for degration of Red195 dye under ultrasonic/ UVA irradiation	(Zamani et al., 2023
Red Algae	Green Synthesis	Co_3O_4	NR	NR	Cytotoxicity, antioxidant, anticoagulant, antibacterial, and anti-cancer properties	(Ajarem et al., 2022)
Marine red algae	Phyto-synthesis	NiO	NR	45.59	Catalyst	(Moavi et al., 2021)
Ulva fasciata Delile	Chemical Reduction	ZnO	NR	NR	Photocatalytic activity of of MB dye	(Fouda et al., 2022)
Spirulina platensis	Bio-templating	Ni@ZnO@ZnS	3.21 ± 0.09 - 2.85 ± 0.09 eV	79.1	Photocatalysts for efficient solar water decontamination and bioethanol production	(Serrà, Artal, et al., 2020)
Chlorella pyrenoidosa	Hydrothermal treatment and bio-templating	Fe_3O_4–TiO_2	NA	NA	Photocatalytic activity of Rhodamine B (RhB) degradation under visible-light irradiation	(Mu et al., 2019)

NA: Not Available ; NR: Not Reported ; NPs: Nanoparticles

Various algae-based photocatalyst preparation methods have been explored in recent years for the synthesis of nanoparticles (NPs) and composites to enhance photocatalytic performance. As shown by **Table 2**, different algal species and preparation techniques result in photocatalysts with varying characteristics like reduced band gap energy, increased surface area, and diverse applications.

Table 2 summarizes key details related to the algal species used, photocatalyst preparation method, NPs synthesized, band gap reduction, surface area, applications, and associated references for eight recent studies employing algae-based biosynthetic methods. Methods like hydrothermal treatment, chemical reduction, sol-gel technique, carbonization, and bio-templating using algal extract or biomass have been utilized to produce photocatalysts containing metal oxides, metal sulfides, or metal NPs. The resultant composites showed enhanced visible light absorption, surface area as shown in **Figure 8**, and photocatalytic degradation of dyes and phenols under UV, visible, or solar light irradiation. Some also displayed improved cytotoxic, antibacterial, or antioxidant effects with potential multifunctional applications.

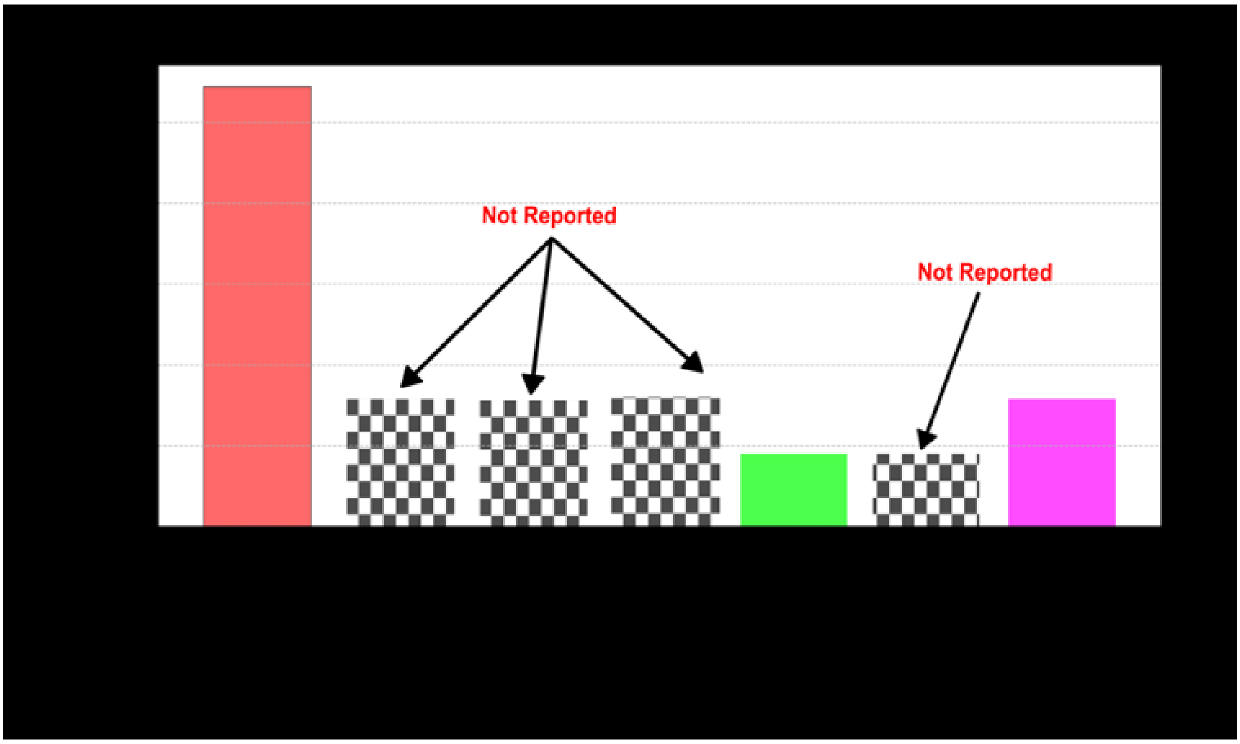

Figure 8. Distribution of Applications and Algal Species

As shown in **Table 2**, various microalgae and macroalgae species including *Chlorella*, *Tetradesmus*, *Scendesmus*, red algae, *Ulva*, and *Spirulina* have been recently utilized as biofactories for nanoparticle synthesis and photocatalyst preparation. Both freshwater and marine algae seem to be suitable candidates offering reducing, capping, and stabilizing biomolecules for biogenic non-toxic approaches. Through methods like hydrothermal treatment, chemical reduction using algal extracts, or direct bio-templating using algal biomass, metal and metal oxide nanoparticles of TiO_2, Fe_3O_4, Co_3O_4, NiO, ZnO, ZnS as well as composites like algae/Fe_3O_4/TiO_2 have been biosynthesized.

The table indicates substantial reductions in band gap energy by 0.6 - 1 eV for the *Chlorella*, *Tetradesmus* and *Spirulina* derived photocatalysts, enabling visible light absorption. Photodegradation of dyes like rhodamine B, reactive red 195, and methylene blue was demonstrated using several algal photocatalysts under UVA, visible, or solar light irradiation. Some also offered antibacterial effects (Co_3O_4) or antioxidant properties while applied as nanocoatings (NiO). Optimization of key parameters as shown in **Figure 9** like algal extract dose, metal salt concentration, calcination temperature, and catalyst loading still needs further investigation for improved morphological control, appropriately matched conduction band positions, higher surface areas of >100 m^2/g, better interfacial charge transfer, and multi-functionality integrating wastewater remediation with value-added products like biofuels.

Chlorella pyrenoidosa to Photocatalytic Activated Charcoal

Chlorella pyrenoidosa has been used as a biofactory for metal nanoparticle production and as a support structure during photocatalyst preparation via hydrothermal technique or activation/carbonization (Figueiredo et al., 2020). Figueiredo et al. (2020) exploited the residual biomass of *Chlorella pyrenoidosa* microalgae for synthesis of a carbonaceous photocatalyst via an activation/carbonization process. The algal biomass was first dried and then activated by heating to temperatures between 10-600°C.min^{-1} under inert atmosphere for 240 minutes. This thermal treatment carbonizes the organic components and develops a highly porous structure, while physical or chemical activation employing acids introduces additional surface groups. The resultant activated biochar exhibited a porous network with very high 272 m^2/g surface area along with changes in crystalline phases as evidenced by XRD and functional groups as shown by FTIR analysis. The high porosity and surface groups promote adsorption while the carbonaceous material also allows visible light absorption enabling dye degradation. A zeta potential of -0.4±1.2 mV indicated stable suspensions. Under UV irradiation, 75.5% Rhodamine B dye degradation was achieved in 120 mins using this *Chlorella* activated charcoal photocatalyst, only slightly lower than 92.5% degradation by commercial ZnO. The key advantage however was 66.5% dye degradation under visible light compared to just 16.6% by ZnO, demonstrating its higher visible-light photocatalytic activity. Process optimization to control porous structure and surface chemistry is important for further enhancing efficiency. This was converted to an efficient carbonaceous photocatalyst able to degrade rhodamine B dye under UV and visible irradiation via generation of reactive oxygen species (Figueiredo et al., 2020).

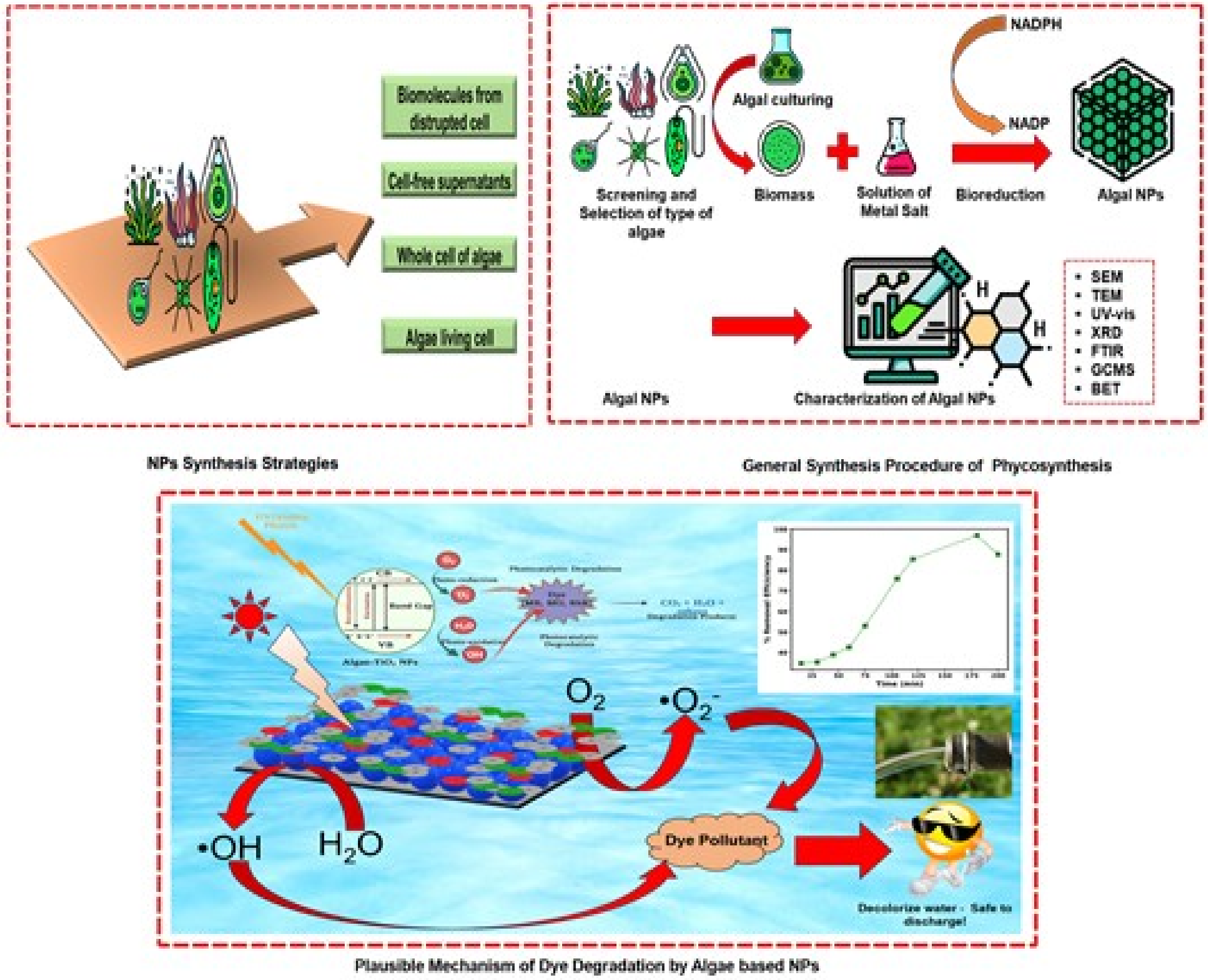

Figure 9. The Algal based NPs synthesis strategies, Phycosynthesis General Synthesis Process, and Application Dye Contaminant Removal of Algal-TiO_2NPs.

Macroalgae–Marine Red Algae with NiO NPs

Marine red macroalgae have also shown biogenic potential for metal oxide nanoparticle synthesis (Moavi et al., 2021). Moavi et al. (2021) have demonstrated a green biogenic approach for NiO nanoparticle synthesis exploiting marine red algal extracts likely containing bioactive phytochemicals. A nickel precursor solution was simply stirred with the algal extract at 60°C which likely results in the reduction of metal ions to zerovalent Ni as well as stabilization by attachment of algal components onto formed nuclei. A subsequent annealing step facilitates oxidation and crystallization to obtain spherical NiO nanocrystals of around 32 nm size confirmed by XRD and TEM. FTIR reveals signatures of extract derived organic constituents like polysaccharides still present as coatings even after washing. This is also clear from TGA analysis which shows a 14% and -41% mass loss attributable to surface bound biological components that provide stability in suspensions. Importantly, the NiO nanoparticles presented very high 45.59 m^2/g BET surface area, almost 46-fold higher than bulk NiO, indicating additional porosity, defects, and abundance of surface catalytic sites. When applied as a nanocatalyst for organic synthesis, excellent yields up to 96% were accomplished highlighting the utility of such biogenic metal oxides for sustainable applications including waste remediation.

Macroalgae–Red Algae with Co_3O_4 NPs

Another study by Ajarem et al. (2022) continuously stirred cobalt nitrate solution with red algal extract for bio-synthesis of Co_3O_4 nanoparticles. The NPs demonstrated cytotoxic, antibacterial, antioxidant, and anticoagulant properties suitable for multifunctional biological and environmental applications (Ajarem et al., 2022). Such marine algal extracts seem to contain bioactive phytochemicals like polysaccharides, flavonoids, proteins, pigments, and terpenoids that can act as effective capping and stabilizing agents favoring nanoparticle synthesis. Ajarem et al. (2022) demonstrated an eco-friendly approach for cobalt oxide (Co_3O_4) nanoparticle preparation using aqueous extracts from red algae, which likely contain bioactive phytochemicals like polysaccharides and pigments. Simply mixing the algal extract with cobalt nitrate solution, stirring at room temperature, and incubating for 24 hours resulted in bioreduction and formation of Co_3O_4 nanoparticles indicated by the color change perceived. The color change observed from pale pink to dark brown indicates Co^{3+} to Co^{2+} conversion mediated by reducing sugars or antioxidants in the extract. Bio-stabilization is also provided by adhesion of algal components onto nanoparticle surfaces as confirmed through FTIR. XRD revealed crystalline Co_3O_4 NPs with average size around 29 nm, corroborated by TEM and SEM imaging showcasing near spherical morphology. EDAX signals corresponding to cobalt and oxygen signify purity. When assessed for bio-applications, excellent antibacterial activity was demonstrated with zones of inhibition comparable or better than antibiotic standard oxytetracycline. Appreciable free radical quenching capacity reflective of antioxidant properties was also evidenced along with significant cytotoxicity against cancer cells. Moreover, remarkable anticoagulant and thrombolytic functions were displayed in human blood samples, expanding the therapeutic scope of such biogenic nanoparticles. Therefore, the red algae mediated synthesis offers a sustainable platform for simple and scalable production of multifunctional Co_3O_4 nanocrystals.

Tetradesmus obliquus as bio-TiO_2

Tetradesmus obliquus microalgae was exploited by Guo et al. (2023) for the fabrication of bio-templated TiO_2 using a bionic freeze-drying approach (Guo et al., 2023). The algal cells likely served as biotic scaffolds that favored TiO_2 nanoparticle nucleation and growth within their network, resulting in sheet-like bio-TiO_2 with 3D interconnected pores after annealing. A 0.14 eV band gap reduction was achieved along with efficient visible light driven photocatalytic degradation of phenols. Such biogenic mineralization routes integrating freeze drying offer green chemistry benefits through avoiding hazardous chemicals and requiring low energy input. Guo et al. demonstrated an innovative bio-templating method for preparation of titanium dioxide nanoparticles using *Tetradesmus obliquus* microalgae. The algal cells likely serve as biotic scaffolds guiding the nucleation and growth of TiO_2 nanocrystals within their network through a bionic freeze-drying process. Specifically, titanium precursor solution was added to algal suspensions containing amino acids L-arginine and L-cysteine. Interaction of the Ti ions with algal cells and biomolecules leads to formation of titanium hydroxide nuclei. Subsequent freeze drying of these suspensions facilitates orientation and assembly of TiO_2 primary crystals along patterned networks of the algal cells.

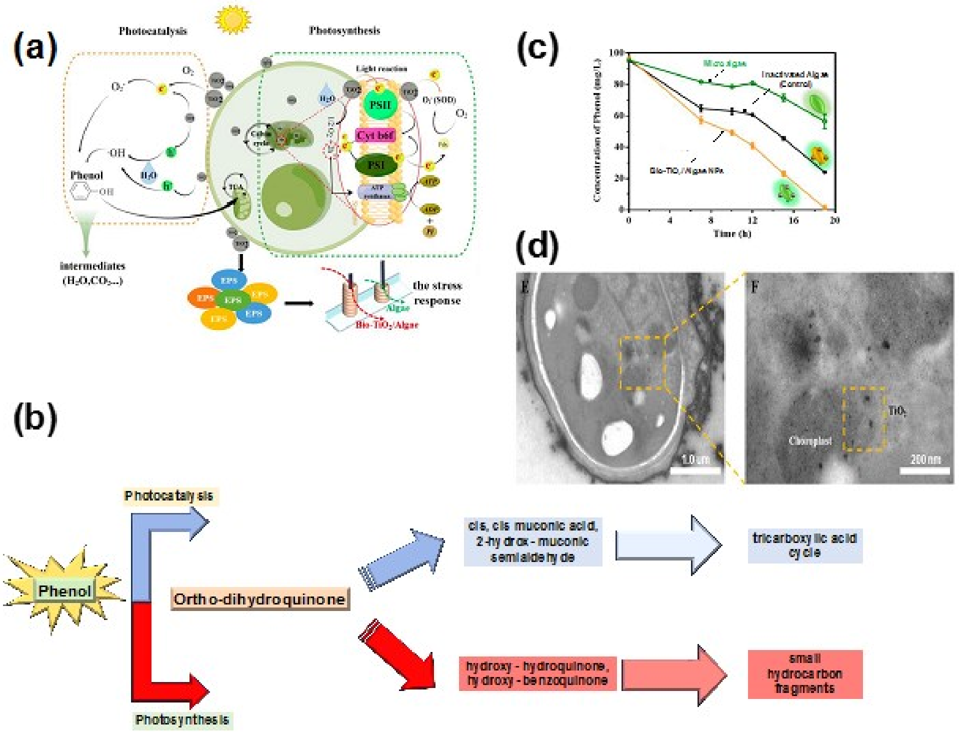

Figure 10. The illustrative visualization of **(a)** Plausible synergetic mechanism of Bio-TiO_2/Algae in phenol degradation scheme, **(b)** The proposed pathway of Phenol degradation process through photocatalysis and photosynthesis process by Bio-TiO_2/Algae, **(c)** Result of phenol photocatalytic degradation, and **(d)** HRTEM (High-Resolution Transmission Electron Microscope) observation result with enlargement of microalgae cell internal structure (adopted and modified from Guo et al. (2023) is licensed under CC BY 4.0)

Final annealing crystallizes anatase TiO_2 nanoparticles embedded within the algal biomass matrix. This bio-TiO_2 complex exhibits excellent biocompatibility and forms a synergistic system with the microalgae, boosting visible light driven photocatalytic degradation of phenols as illustrated by **Figure 10**. The bio-templating synthesis enables scaling up while benefiting from narrower band gap around 3.1 eV from 3.24 eV, suppressed charge recombination, and accelerated interfacial electron transfer evidenced from bandgap empirical formula. The approach offers green, low-cost and efficient means for wastewater remediation.

Green Macroalgae–*Ulva fasciata* with ZnO NPs

The marine green macroalga *Ulva fasciata* was utilized by Fouda et al. (2022) for ZnO nanoparticle synthesis via chemical reduction technique. Fouda et al. (2022) demonstrated a facile biomimetic approach for ZnO nanoparticle preparation exploiting the aqueous extract of *Ulva fasciata* seaweed (Fouda et al., 2022). Mixing the zinc salt precursor with algal extract likely containing reducing sugars, pigments, and proteins, followed by heating and incubation facilitates bioreduction to zerovalent zinc and subsequent oxidation to ZnO nanocrystal formation. Bioactive components further provide capping/stabilization by adherence onto nanocrystallite surfaces as confirmed through characterization process. XRD signals corroborate ZnO formation while UV-vis absorption edge around 325 nm indicates quantum confinement consistent with TEM visualization of 3-33 nm sized spherical nanoparticles. EDX signals from SEM verify presence of Zn and O elements signifying purity. An efficient antibacterial activity against both Gram positive and negative pathogens was accomplished with inhibition zones up to 21.7 mm. As a nanocatalyst for organic dye degradation, 84.9% methylene blue removal was achieved in 140 mins under visible light irradiation showcasing high efficacy and reusability sustaining performance over six cycles. Furthermore, outstanding 96.1% decolorization of real tannery wastewater was attained along with major reduction in COD, BOD, TSS, conductivity and notably 93.4% elimination of toxic Cr(VI) content, highlighting environmental applicability.

Cyanobacteria–*Spirulina platensis* as Ni_2ZnO_2ZnS Photocatalyst

Cyanobacteria like *Spirulina platensis* also possess bioreducing potential suitable for synthesis of composite nanomaterials as demonstrated by (Serrà, Artal, et al., 2020). Serrà, Artal, et al. (2020) demonstrated an innovative biogenic approach exploiting the helical biomass of *Spirulina platensis* cyanobacteria for direct synthesis of a tri-component Ni_2ZnO_2ZnS photocatalyst. The microalgae cells likely serve as 3D biomorphic templates guiding the nucleation and conformal deposition of the metal/metal oxide nanolayers through their sequential reduction from aqueous precursors. First, the algal cells are pretreated by fixation using glutaraldehyde to retain structural integrity. Activation using Pd catalysts facilitates Ni shells to be uniformly coated onto the cells through an electroless plating process. Further chemical bath deposition helps deposit exterior ZnO and ZnS layers in an onion-like arrangement. Strong interfacial adhesion and interactions between the Spirulina biomatrix and the inorganic nanolayers is indicated. The unique helical morphology and hierarchical hybrid nanostructure provides enhanced light harvesting capacity and efficient charge carrier separation. XRD confirms the crystalline phases while UV-vis absorption edge shows substantially reduced bandgap to 2.85 eV with BET surface area of 79.1 m^2/g enabling solar driven photocatalysis. MB dye mineralization efficiency exceeding 99% is accomplished under sunlight. The microalgae skeletons can be conveniently recycled after photocatalyst usage to directly produce bioethanol via fermentation owing to their glycogen content. The sustainable process integrates wastewater remediation with biomass valorization in a carbon-neutral circular bioeconomy approach.

The photocatalytic performance of the algae-derived nanomaterials in **Table 2** is governed by several aspects of the biosynthetic processes utilized and resultant characteristics. The choice of green algal species impacts biocompatibility and bio-templating ability during nanoparticle nucleation while seaweed and microalgae extracts provide bioactive reducing and stabilizing agents. Preparation conditions like hydrothermal, sol-gel and carbonization temperatures control morphology and surface areas, with higher temperatures typically improving crystallinity. Bandgap reduction achieved through synthetic techniques or algal scaffolds enables visible light absorption for superior photocatalytic dye/pollutant degradation under solar irradiation versus UV-dependence. Composite configurations also assist efficiency via synergistic functions of metal/oxide components e.g. Ni islands in Ni_2ZnO_2ZnS system acting as co-catalysts for charge transfer. Higher surface areas above 100 m^2/g provide abundant reactive and adsorption sites. Multicomponent heterojunction nanostructures facilitate spatial charge separation over recombination, also offered by 3D algal cell scaffolds while surface defects promote reaction with adsorbates. Optimization of key synthetic parameters like extract doses, precursor concentrations and post-processing is vital for crystalline phase purity, particle size distribution, surface chemistry and overall catalytic performance. Further mechanistic insights would assist designing bespoke novel bio-photocatalysts.

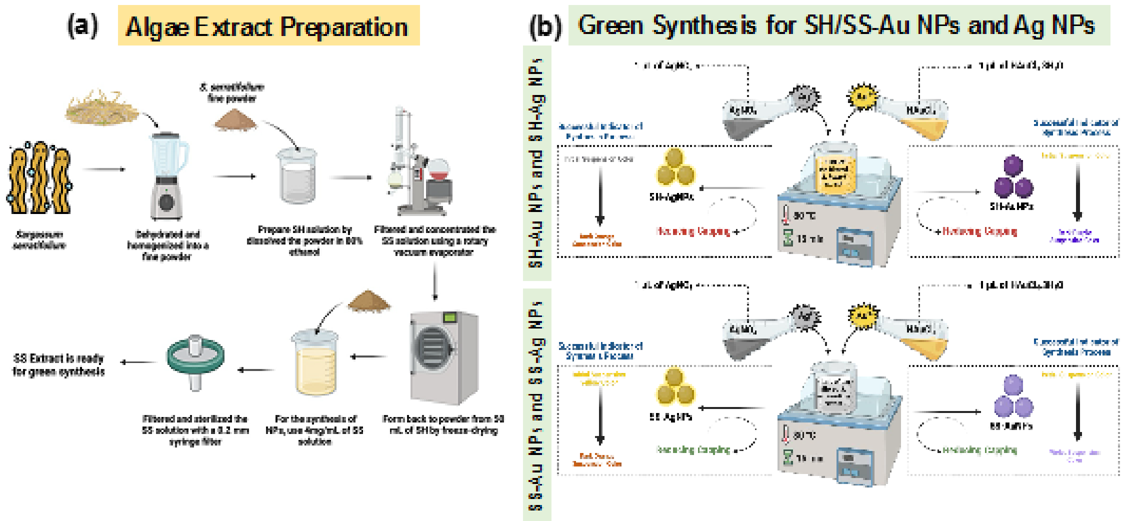

Figure 11. The schematic representation of **(a)** preparation of SH/SS extract for green synthesis of NPs and **(b)** The procedure of bio-fabrication of SH/SS-Au NPs and SH/SS Ag NPs (where SH/ss during the formation of NPs extract acted as reducing and capping agents) (adopted and modified from Kim et al. (2021) is licensed under CC BY 4.0)

Phyco-synthesis as Novel Photocatalyst: Parameters of Photocatalytic Performance

The biogenic preparation of algae-templated nanocomposites and their photocatalytic performance is governed by several crucial parameters. The choice of appropriate metal/metal oxide precursors and their concentrations determines the conversion efficiency, particle sizes, and morphologies (Osman et al., 2024). Temperature, pH, and duration of synthesis steps like bioreduction, annealing, sulfidation etc. allow tuning physical dimensions and crystalline phases (Mourdikoudis et al., 2018) as shown by **Figure 11**. Capping agents present in algal extracts control the stabilization, surface defects as well as band bending and electron transfer rates (Chugh et al., 2021). Algal species selected, their cell wall/EPS compositions, metabolites and secretions influence biocompatibility, processabilities, and recycling potentials. Drying methods affect porosities and surface areas available for adsorption and reactions. Facet exposures, heterojunctions, and hierarchical nanoarchitectures promote directional transfer, mobility and separation of photogenerated charge carriers over recombination (Balan et al., 2023). Interfacial binding in multilayered hybrids also assists exciton migration to reactive sites. Appropriate post-synthesis processing like washing, filtration and centrifugation is vital to remove impurities and unstable constituents. Moreover, calcination and hydro/solvothermal treatments allow generation of desired carbonaceous, oxide and sulfide phases. Total efficiency is reliant on optimized synergistic interactions between light-harvesting components, electron mediators, adsorption/reaction sites etc. The photodegradation efficiency also can be varied based on contact time and the NPs dosage used as illustrated by **Figure 12**. Further accuracy in control of synthetic factors as mentioned above through response surface models would pave the way for tailored, scalable and sustainable photocatalysts which enhanced the performance of Algal NPs photocatalytic activity.

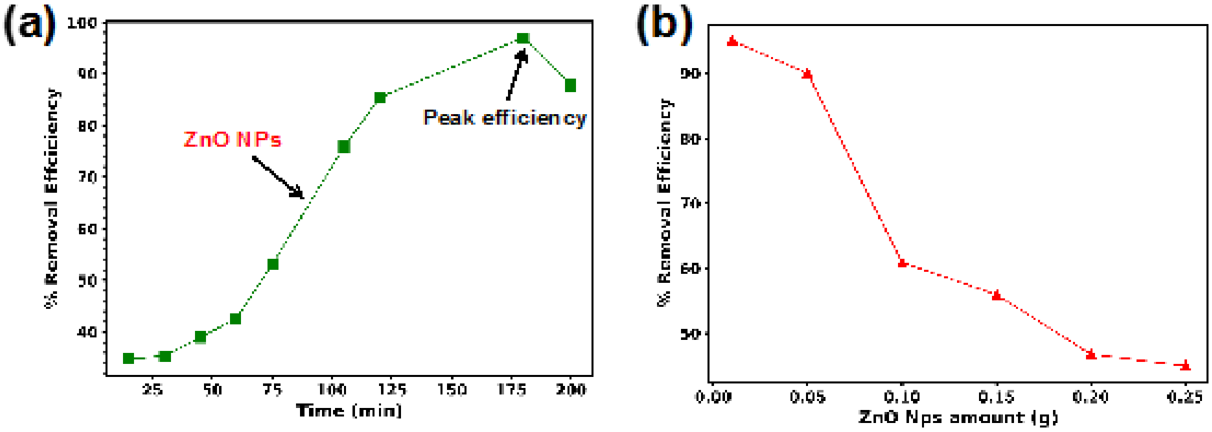

Figure 12. The schematic representation by result of **(a)** Influence of time on elimination amount of DBT using green ZnO NPs and **(b)** Influence of concentrations of ZnO NPs on elimination amount of DBT (adopted and modified from Khalafi et al. (2019) is licensed under CC BY 4.0)

Environmental Remediation Benefit of Phyco-synthesis: Photocatalysis Applications

Photocatalysis holds tremendous potential for environmental remediation and sustainability across diverse areas as shown by **Figure 14**. Significant applications exist in air treatment - photocatalysts can effectively eliminate hazardous pollutants like ethylene, VOCs, and microbes from storage facilities, contaminated sites, indoor spaces, and gaseous emissions to enable cleaner air. Another major application is in water treatment, wastewater purification, and solar-driven photocatalytic processes can mineralize stubborn organic and microbial contaminants to benign inorganic end products as explained in **Figure 13**.

Self-cleaning photocatalytic coatings on active surfaces such as construction materials, textiles, and water filtration membranes can also mitigate biofouling and degradation over time for enhanced lifespan. Photocatalysis further enables green chemistry by facilitating renewable chemical synthesis routes with improved eco-efficiency. On the energy front, photocatalytic water splitting and CO_2 reduction provide exciting possibilities for sustainable solar fuel and chemicals production. Inclusively, the versatility of photocatalysis across pollution mitigation, self-cleaning smart materials, green synthesis, and solar energy harvesting makes it indispensable for sustainable development manifestation. With ongoing advances in nanocatalyst optimization, reactor engineering, and process integration, the real-world promise of photocatalytic systems will greatly benefit environmental quality along with economic growth.

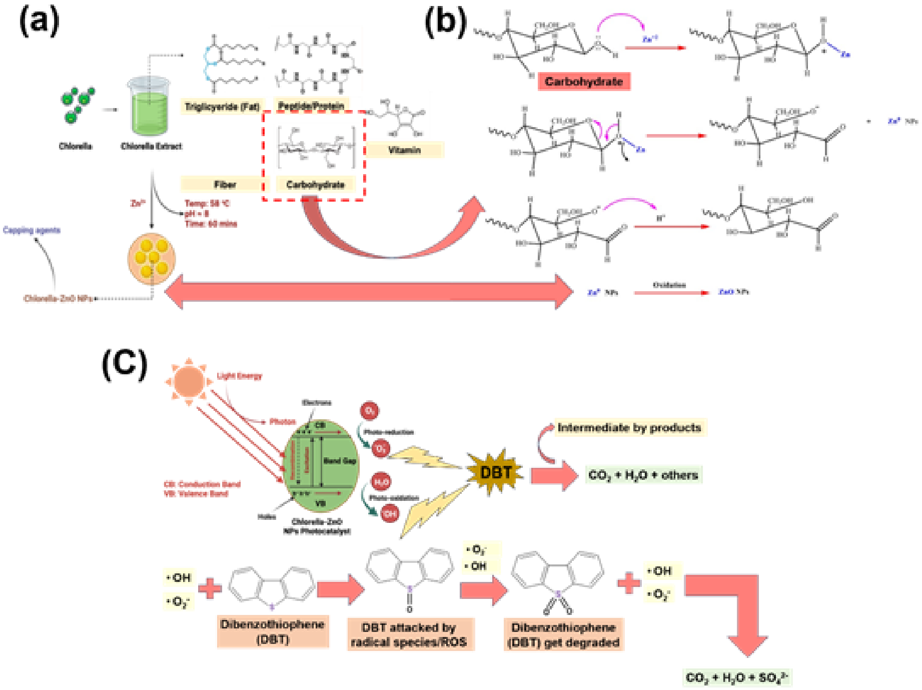

Figure 13. The schematic representation of **(a)** The biosynthesis procedure of utilization of *Chlorella* extract with ZnO to produce *Chlorella*-ZnO NPs photocatalyst material, **(b)** The plausible mechanism of carbohydrate as bioreducing agent derived from *Chlorella* for biosynthesis of *Chlorella*- ZnO NPs and **(c)** Plausible mechanism of photo-desulfurization for organosulfur pollutant, DBT (Dibenzothiophene) by using the *Chlorella*-ZnO NPs as result of biosynthesis process (adopted and modified from Khalafi et al. (2019) is licensed under CC BY 4.0)

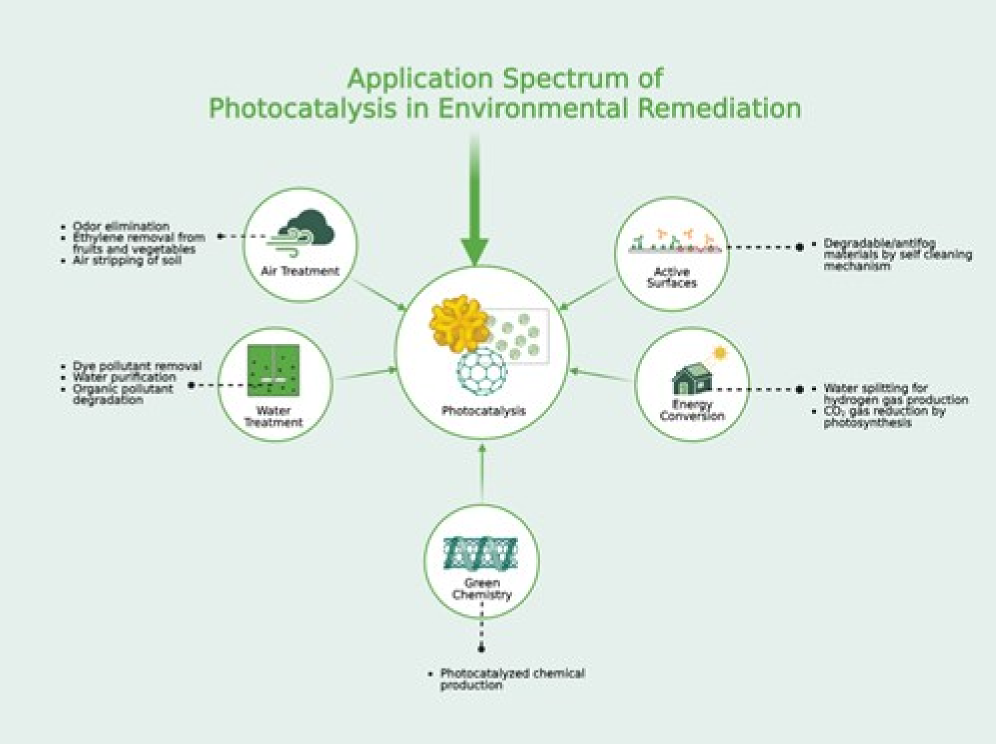

Figure 14. Photocatalysis Applications (The figure was fully drawn by BioRender).

Heavy Metal pollutant removal capability of Algal based NPs

The utilization of algae-based nanoparticles (NPs) for removing heavy metal pollutants from wastewater has garnered substantial interest in recent years. Algae provide a sustainable and renewable biomass source for synthesizing NPs with unique physiochemical properties that enable efficient heavy metal adsorption. The utilization of algae for the synthesis of nanoparticles is an emerging field that holds great promise for heavy metal remediation. Algae provide natural reducing and capping agents (Song et al., 2022) as shown by **Figure 11**, allowing for an eco-friendly approach for Bio-NPs fabrication. Moreover, the high surface area and specificity of nanoparticles make them well-suited for absorption of heavy metal contaminants.

Multiple studies have investigated the performance of algal NPs made from metals like silver (Ag), gold (Au), iron oxide (FeO), and titanium dioxide (TiO2) in eliminating common heavy metal contaminants including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), chromium (Cr), and lead (Pb) from wastewater samples contaminated by heavy metals.

Table 3. Phycosynthesis application for heavy metal remediation

Algal Species	Nanoparticles used	Heavy metal removed	Reduction efficiency (%)	Ref.
Laurencia papillosa	Ag	Fe	97.1	(El Shehawy et al., 2023)
Laurencia papillosa	Ag	Mn	43.3	(El Shehawy et al., 2023)
Laurencia papillosa	Ag	Zn	5.6	(El Shehawy et al., 2023)
Laurencia papillosa	Ag	Cu	2.4	(El Shehawy et al., 2023)
Algae (Chitosan nanofiber)	Algae-TiO_2/Ag	Cr(VI)	91[1]	(L. Wang et al., 2017)
Chlorella vulgaris	Au	Pb	57.41	(Adenigba et al., 2020)
Chlorella vulgaris	Ag	Pb	66.10	(Adenigba et al., 2020)
Nannochloropsis sp	Au	Pb	66.53	(Adenigba et al., 2020)
Nannochloropsis sp	Ag	Pb	68.86	(Adenigba et al., 2020)
Spirulina platensis	FeO	Cr	75.26	(Mohan et al., 2021)

[1] at pH 2.0

As shown by **Table 3**, algal NPs demonstrate excellent removal capacity for different heavy metal species. For instance, silver NPs synthesized using the macroalgae *Laurencia papillosa* were able to reduce Fe concentrations by 97.1%, though they exhibited poorer elimination of other metals like Mn (43.3%), Zn (5.6%), and Cu (2.4%) (El Shehawy et al., 2023). The superior Fe removal may be attributable to the high ionic radius and electronegativity of Fe enabling stronger electrostatic attraction and bonding with the Ag NPs. Interestingly, another study found that composite algal-TiO_2/Ag NPs could decrease Cr(VI) concentrations in chromium-contaminated groundwater by up to 91% (L. Wang et al., 2017). The exceptionally high Cr(VI) removal efficiency is likely due to synergistic effects between TiO_2 photocatalysis and AgNP adsorption. Different algal species including *Chlorella vulgaris, Nannochloropsis* sp., and *Spirulina platensis* have also shown promise for synthesizing gold and silver nanoparticles with over 50% lead (Pb) removal efficiency (Adenigba et al., 2020; Mohan et al., 2021).

The red alga *Laurencia papillosa* was utilized for green synthesis of silver nanoparticles (Ag NPs) by El Shehawy et al. (2023). The nanoparticles demonstrated excellent removal capacity for iron at 97.1% efficiency. The high surface-to-volume ratio and presence of capping agents likely facilitated adsorption and subsequent reduction of the iron ions. Other mechanisms such as ion exchange and complexation with functional groups on the nanoparticles may have also contributed. However, the efficacy was much lower for other metals like manganese, zinc, and copper. This selectivity suggests specificity in the interaction between the nanoparticle properties and the physicochemical characteristics of each heavy metals ion.

Another combination utilizing algal biomass for nanoparticle fabrication is the use of chitosan-algae nanofibers with incorporated TiO_2 and silver nanoparticles synthesized by Wang et al. (2017). This system achieved 91% removal of the priority toxic pollutant hexavalent chromium. The high porosity of the nanofibers promotes adsorption, while the TiO_2 likely mediated redox transformations facilitating chromium reduction and precipitation. Also, the antimicrobial properties provided by silver nanoparticles may have also enhanced removal viability through antibacterial action against chromate reducing bacteria.

In work by Adenigba et al. (2020), microalgae including *Chlorella vulgaris* and *Nannochloropsis* sp. were studied for synthesizing gold and silver nanoparticles. Efficacies over 60% were achieved for lead (Pb) sequestration. Biosorption is likely the primary mechanism, whereby passive binding of lead ions takes place at the nanoparticle surfaces enriched by the algal biomolecules serving as capping/stabilizing agents. Specific functional groups like amines, carboxylates, and sulfonates known to chemisorb metal ions are likely involved. The slight variability in lead removal between gold and silver nanoparticles points to differences in metal-sorbate interactions dependent on nanoparticle size, morphology, aggregation, etc.

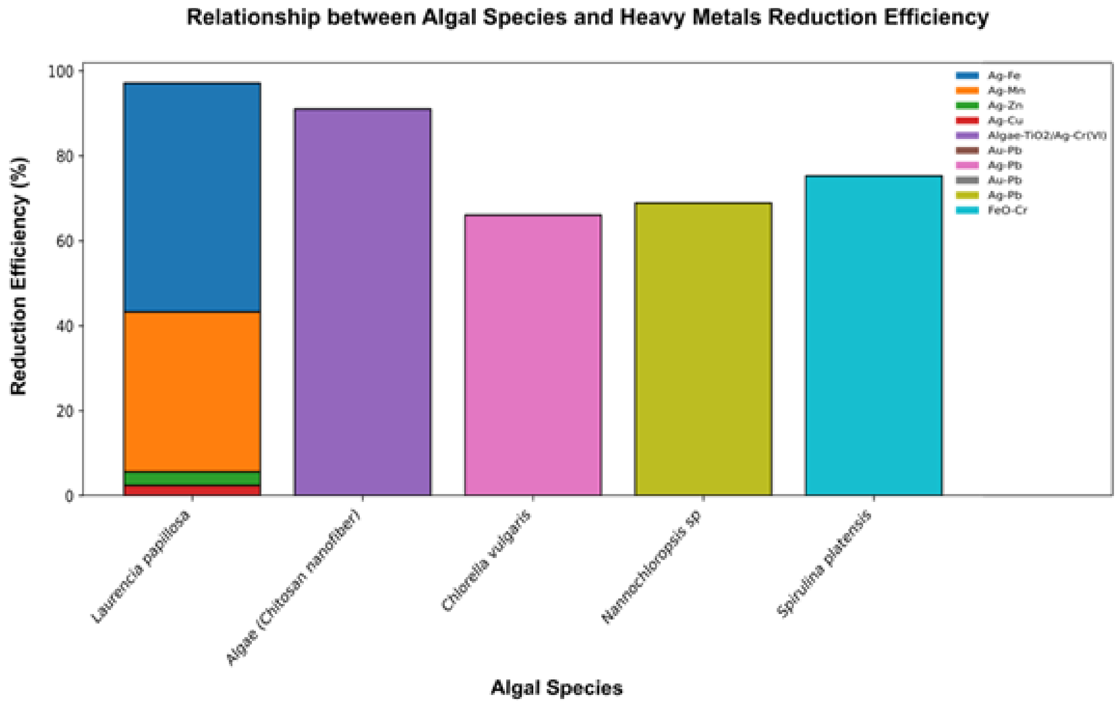

Figure 15. Heavy Metal Reduction distribution by algal species

Dye removal capability of Algal based Photocatalyst

The use of algal biomass for the synthesis of nanoscale photocatalysts is an expanding and emerging area of research on sustainable chemistry and engineering. Algae provide a renewable feedstock along with reducing and capping agents to facilitate clean fabrication of nanoparticles. Such algae-based nanocomposites often demonstrate enhanced functionality and specificity for applications like photodegradation of toxic textile dyes present in wastewater as shown by **Figure 16**. The use of algae as biofactories for synthesizing metal and metal oxide nanoparticles is an expanding area of interest for environmental remediation of dyes/colorants from wastewater. Algae provide natural capping and stabilizing agents which facilitate crystallization of nanoparticles with small, uniform sizes optimal for high reactivity as photocatalysts. Upon exposure to light, electron-hole pairs are generated on the nanoparticle surface leading to production of reactive oxygen species. These oxidize dye pollutants into smaller less toxic molecules. **Table 4** compiles research on various algal sources for nanoparticle synthesis and their efficacy in decolorizing common industrial dyes.

Table 4. Phycosynthesis application for dye pollutant remediation

Species of Algae	**NPs synthesized and produced**	**Dye removed**	**Removal efficiency (%)**	**Ref.**
Syringodium isoetifolium	TiO_2	Methylene blue	83	(Sundar et al., 2024)
Syringodium isoetifolium	TiO_2	Methylene orange	58	(Sundar et al., 2024)
Asterarcys quadricellulare	CuO	Bismarck Brown Y (BBY)	95.78	(Khandelwal et al., 2023)
Asterarcys quadricellulare	CuO	Brilliant Green (BG)	98.02	(Khandelwal et al., 2023)
Asterarcys quadricellulare	CuO	Eriochrome Black T (EBT)	94.15	(Khandelwal et al., 2023)
Asterarcys quadricellulare	CuO	Malachite Green (MG)	96.04	(Khandelwal et al., 2023)
Sargassum horneri	Ag	Methylene blue	NA**	(Song et al., 2022)
Sargassum horneri	Ag	Rhodamine B	NA**	(Song et al., 2022)
Sargassum horneri	Ag	Methyl Orange	NA**	(Song et al., 2022)
Sargassum horneri	Au	Methylene blue	NA**	(Song et al., 2022)
Sargassum horneri	Au	Rhodamine B	NA**	(Song et al., 2022)
Sargassum horneri	Au	Methyl Orange	NA**	(Song et al., 2022)
Caulerpa racemoedisosa	Ag	Methylene Blue	NA	(Edison et al., 2016)
Turbinaria conoides and *Sargassum tenerrimum*	Au	Organic Dye Molecules	NA	(Ramakrishna et al., 2016)
Chlorella pyrenoidosa	Ag	Methylene Blue	70	(Aziz et al., 2015)
Hypnea musciformis	Ag	Methyl Orange	NA	(Ganapathy Selvam & Sivakumar, 2015)
Sargassum vulgare	Zn	Methylene Blue	87.59	(Karkhane et al., 2020)
Sargassum myriocystum	Ag	Methyl Orange	98	(Balaraman et al., 2020)

Species of Algae	NPs synthesized and produced	Dye removed	Removal efficiency (%)	Ref.
Ulva lactuca	Ag	Methylene Blue	NA	(Kumar et al., 2013)
Chlamydomonas reinhardtii	CdS	Red195	90	(Rao & Pennathur, 2017)
Scendesmus sp	Scendesmus/Fe_3O_4/TiO_2	Methylene Blue	100	(Zamani et al., 2023)
Sargassum coreanum	Ag	Reactive Blue 198	>99	(Somasundaram et al., 2021)
Padina gymnospora	CdO-ZnO (SCZ)	Methyl Orange	99.57, 95.2 and 94.3	(Rajaboopathi & Thambidurai, 2017)
Chlamydomonas reinhardtii	ZnO	Methylene Blue	95	(Rao & Gautam, 2016)
Chlorella pyrenoidosa	Synthesized as activated charcoal	Rhodamine B (RhB)	75.5 (under UV) and 66.5 (under visible light)	(Figueiredo et al., 2020)
Ulva fasciata Delile	ZnO	Methylene Blue	84.9 ± 1.2 (under UV light) and 53.4 ± 0.7 (under the dark)	(Fouda et al., 2022)
Ulva fasciata Delile	ZnO	Tanning Wastewater	96.1 ± 1.7	(Fouda et al., 2022)
Chlorella pyrenoidosa	Fe_3O_4–TiO_2	Rhodamine B (RhB)	99.8	(Mu et al., 2019)

NA: Not Available
NA**: The authors concludes that the removal efficiency as *extremely effective*

As shown in **Table 4**, various algal species have been utilized to produce eco-friendly photocatalytic nanoparticles mainly comprised of metal oxides like TiO_2, ZnO, CdO and CuO along with noble metals like silver and gold. High removal efficiencies have been achieved for common cationic and anionic dyes spanning different chemical classes. For example, TiO_2 nanoparticles synthesized using the marine macroalga *Syringodium isoetifolium* showed 83% and 58% removal of the cationic dye methylene blue and anionic dye methylene orange, respectively (Sundar et al., 2024). Another macroalgal species *Asterarcys quadricellulare* was used to fabricate CuO nanoparticles with excellent capability for taking up multiple anionic azo dyes with efficiencies over 94% (Khandelwal et al., 2023). As shown, nanomaterials fabricated using brown macroalgae like *Sargassum* spp. have demonstrated excellent activity. Silver and gold nanoparticles synthesized using *S. horneri* were extremely effective in degrading methylene blue, rhodamine B, and methyl orange under visible light irradiation (Song et al., 2022). Comparably high efficacies have been achieved using other algae including the green microalgae *Chlorella* spp. and *Ulva* spp. Interestingly, the nanoparticle composition also impacts efficacy, with silver displaying greater dye removal versus gold in some cases (Song et al., 2022). This points to the role of nanoparticle properties like electronegativity, conductivity, stability, etc. in influencing photocatalysis performance. Elucidating these structure-function relationships can inform rational design of optimal algal-based photocatalytic systems for water purification.

The macroalgae *Sargassum horneri* was used as a biofactory by Song et al. (2022) to synthesize silver and gold nanoparticles which displayed extremely effective photocatalytic dye degradation. The nanoparticles act as light-activated semiconductors, generating electron-hole pairs upon irradiation. The photogenerated electrons reduce dissolved oxygen creating reactive superoxide radicals, while the holes oxidize water to produce hydroxyl radicals. These potent oxygen species then rapidly attack and cleave the dye molecules. Thus, the nanoparticles provide a high surface area for adsorption of dye molecules, concentrating them near the catalyst surface and facilitating oxidation. The algal compounds likely contribute as stabilizers preventing nanoparticle aggregation for sustained catalytic activity.

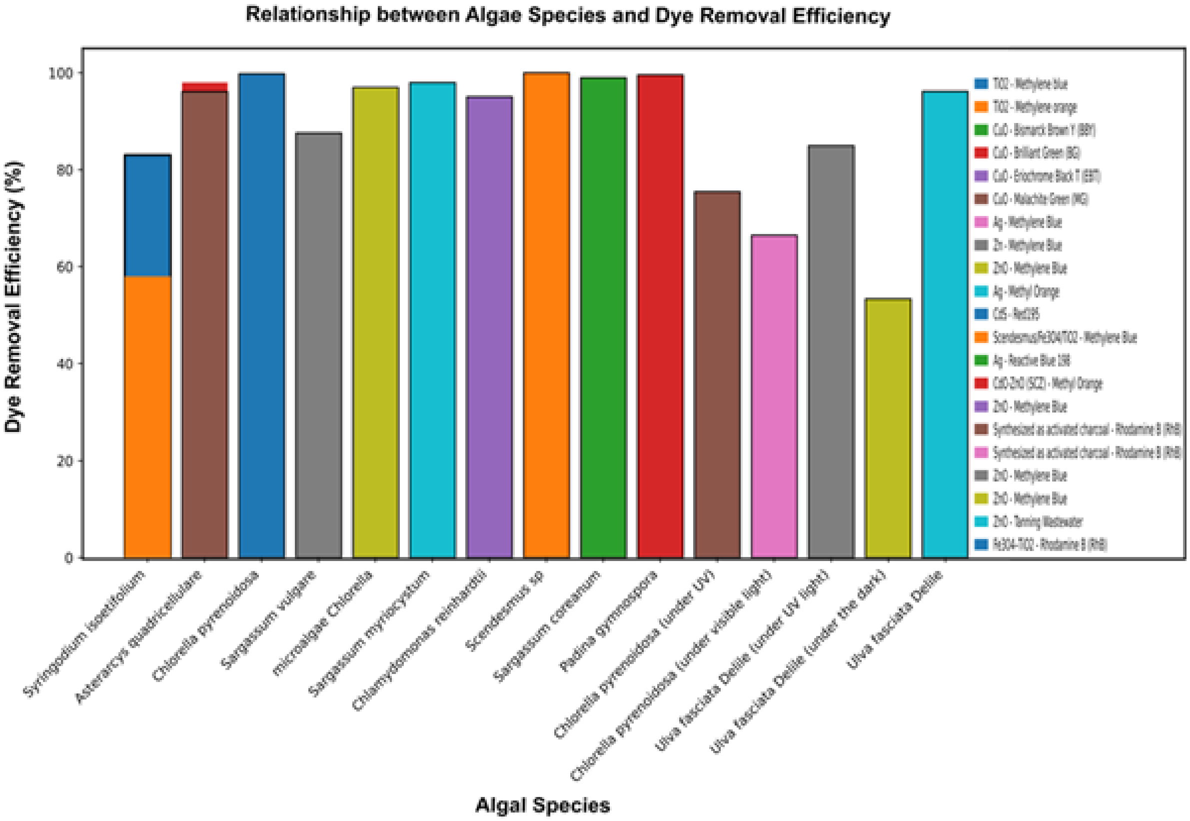

Figure 16. Dye removal distribution by algal species

Another species of algae, *Asterarcys quadricellulare*, was used for synthesizing CuO nanoparticles by Khandelwal et al. (2023). Nearly complete removal was achieved for multiple cationic and anionic dyes. The CuO nanoparticles again function as light-activated photocatalysts, generating electron-hole pairs. Here the dye molecules directly inject electrons into the conduction band of CuO, becoming oxidized radicals which then undergo ring-opening and further degradation. The algal extracts provide bioactive capping agents controlling CuO nanoparticle size and morphology for optimized photocatalytic performance.

Transitioning to green algae, *Chlorella* sp. has been widely studied for dye removal. Microalgae *C. pyrenoidosa* was used by Mu et al. (2019) for fabrication of Fe_3O_4-TiO_2 nanoparticles. A 99.8% rhodamine B removal efficiency was reached. The titanium oxide functions as the primary photocatalyst. Iron oxide extends light absorption via inner filtering effects. The algae provide binding agents controlling nanoparticle size and aggregation. Multiple reactive species like holes, hydroxyl radicals, and superoxides jointly accelerate catalytic dye oxidation.

Looking beyond just efficacy testing, mechanistic studies focused on reactive oxygen signaling, nanoparticle surface interactions, metabolite byproduct characterization, antibacterial action, and sustainability assessments would help strengthen technological development of algal photocatalysts for environmental and water remediation. Analyzing the variability between different nanoparticle compositions and physicochemical properties synthesized across various algal species can elucidate structure-function relationships to further advance this promising and emerging technology for environmental sustainability.

Future Directions

The photocatalytic performance of algae-derived nanomaterials could be further enhanced through several approaches:

1. Doping the nanoparticles with metals or non-metals to modify their electronic band structure and light absorption properties. Transition metals like gold and silver as well as elements such as nitrogen and sulfur have shown promise as dopants to reduce bandgaps or introduce intermediate bands to facilitate visible light photocatalysis.
2. Incorporating co-catalysts like platinum, nickel, and cobalt islands during synthesis to provide electron traps which suppress recombination and promote interfacial charge transfer during photocatalytic reactions.
3. Coupling algae-derived photocatalysts with other nanomaterials like graphene, carbon nanotubes, and conductive polymers to construct heterojunctions and Z-scheme systems. These complex architectures provide pathways for vectorial electron mobility to enhance charge separation.
4. Immobilizing the algal photocatalysts on suitable support substrates to increase mechanical strength, durability, and recyclability. Materials like silica, activated carbon and stainless steel meshes can be explored as viable support matrices.
5. Further structure-function relationship studies through selective doping, facet-engineering, porosity modifications etc. to better understand and optimize synergies between light harvesting, charge transfer, adsorption and interfacial reactivity.
6. Exploring genetic and metabolic engineering approaches to selectively overproduce redox-active components within living algal cells to boost their intrinsic photocatalytic capacity.
7. Techno-economic analyses guiding scale-up to larger pilot-scale synthesis and testing to evaluate real-world operational feasibility and environmental sustainability through life cycle assessments.
8. Expanding the library of algal species tested as photocatalyst sources to uncover new bioactive components and enhanced biogenic synthesis capabilities.

Investigation of reactor and process engineering design aspects like catalyst immobilization modes, irradiance optimization, reaction kinetics modeling etc. for translation into practical and scalable treatment systems.

CONCLUSION

In closing, we successfully evaluated the potential of algae-derived photocatalysts for sustainability and environmental remediation applications by surveying key advances in green synthesis methods, characterization, and performance testing. Diverse algal sources enable green biosynthesis of metal/metal oxide nanoparticles and nanocomposites with tailored properties. Compared to conventional catalysts, these bioinspired systems demonstrate enhanced visible light absorption and charge separation dynamics. Initial proof-of-concept studies exhibited promising results in water remediation, dye degradation, and heavy metal removal. Further mechanistic elucidation is still needed but may guide rational design of higher performance activity materials. Larger scale pilot demonstrations and techno-economic analyses could also help translate these emerging technologies. Ultimately, algae represent an abundant and renewable platform for sustainable photocatalysis bridging materials science and environmental solutions.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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