ISSN: 2287-688X

Annals of
Plant Sciences

Volume 14, Issue 10 (2025) pp. 6992-7004

Review Article

Diatoms in Bioremediation: Quantitative Insights, Mechanistic Advances, and Future Smart Bioengineering Perspectives

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Abstract

Global water pollution has exceeded the critical levels due to unchecked industrialization, agricultural runoff, and domestic waste discharge. The decade has witnessed shifting attention towards microalgae-based systems in the search for sustainable, energy-efficient, and circular remediation technologies. Diatoms (Bacillariophyceae), stand out among them for their unique nanostructured silica frustules, robust photosynthetic efficiency, and adaptability to extreme environmental gradients. This review extensively examines the potential of diatoms in bioremediation across diverse pollutant classes: nutrients, heavy metals, hydrocarbons, dyes, microplastics and pharmaceuticals by integrating quantitative data from recent studies (2015–2025). Species-specific pollutant removal efficiencies are analyzed, with instances like *Nitzschia palea* achieving an impressive 95% phenanthrene removal (10 mg L^{-1}) and *Navicula pelliculosa* eliminating 87% phosphate from municipal wastewater. We have also reviewed mechanistic insights into biosorption, bioaccumulation, enzymatic biotransformation, and diatom bacteria symbiosis in the context of modern nanobiotechnology. The paper further explores emerging frontiers such as diatom-inspired nanomaterials, AI-assisted monitoring, and omics-guided strain optimization. Integrating these capabilities with circular bioeconomy principles could ascertain diatoms as the cornerstone of smart phycoremediation systems capable of mitigating pollution while generating biofuels, nutraceuticals, and biosilica products

Keywords: *Diatoms; Bioremediation; Biosorption; Heavy metals; Microplastics; Pharmaceuticals; Dyes; Hydrocarbons; Nutrient removal; EPS; Biosilica; Biofilm; Photobioreactors; Green technology; Environmental biotechnology.*

Introduction

Global Pollution and the Search for Sustainable Remediation

The explosive rise in industrialization, urbanization, and consumerism has led to excessive pollution of aquatic ecosystems by nutrients, heavy metals, hydrocarbons, pharmaceuticals, dyes, and microplastics (Prata, *et al.,* 2021; Wang, *et al.,* 2023). Conventional wastewater treatments such as coagulation, activated sludge, and membrane filtration, are expensive, energy-intensive, and often ineffective against emerging contaminants (Chisti, 2021). Consequently, phycoremediation, the use of microalgae to purify water, has evolved as an ecological alternative that couples pollutant removal with biomass valorization (Christenson, & Sims, 2011; Rawat, *et al.,* 2016).

Diatoms as Overlooked Champions

Within the broad spectrum of algae, diatoms (Bacillariophyceae) are distinguished due to their silica frustules, metabolic flexibility, and wide distribution across marine and freshwater systems (Round *et al.,* 1990; Nelson *et al.,* 1995). They account for approximately 20 % of global carbon fixation and 40 % of marine primary productivity (McNair *et al.,* 2018). The rigid, nanoporous silica shells of diatoms are structured through

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DOI: 10.5281/zenodo.17513470

silicon - transport proteins (SITs) which provide reactive sites rich in hydroxyl and silanol groups capable of binding diverse metal ions and organics (Martin-Jézéquel *et al.,* 2000; Raven, 1983). Diatoms thrive in a diverse range of climatic conditions tolerating extreme salinity, temperature, and nutrient gradients through physiological plasticity, enabling them to operate in a wide range of wastewater types (Mock & Kroth, 2019; Kilham, *et al.,* 1996).

Their photosynthetic machinery efficiently supports aerobic degradation of organic loads by converting CO_2 into biomass while releasing O_2, (Phang *et al.,* 2015). In nutrient-rich municipal discharges, species such as *Navicula pelliculosa*, *Nitzschia palea*, and *Cyclotella meneghiniana* achieve nitrogen and phosphorus removal rates of more than 90 % (Tripathi *et al.,* 2019; Sharma *et al.,* 2020). The harvested biomass can successively serve as a feedstock for lipids, pigments, and biosilica products, reinforcing the principles of the circular economy (Vassilev *et al.,* 2020; Zhang *et al.,* 2021).

Mechanistic Advantages for Bioremediation

Diatoms coalesce passive and active mechanisms for pollutant attenuation. Their frustule surface mediates biosorption via complexation with Si–OH groups, whereas intracellular pathways enable metal sequestration through metallothioneins and phytochelatins (Cid *et al.,* 2020; Rijstenbil *et al.,* 1994). EPS layers function as adhesive matrices for dyes, microplastics and suspended solids (Al-Thani & Yasseen, 2025). On the other hand, photo-oxidative reactions catalyzed by frustule-associated metals generate reactive oxygen species that degrade hydrocarbons and pharmaceuticals (Radwan *et al.,* 2019; Rummel *et al.,* 2017). These multi-pathway interactions enable diatoms to highly adapt to complex effluent chemistries.

Technological Context and Research Progress

Recent studies engage diatoms in engineered systems such as HRAPs, algal turf scrubbers (ATS), and biofilm photobioreactors to treat municipal, dairy, brewery, and textile wastewater (Craggs *et al.,* 2011; Garfí, *et al.,* 2017; Liu, *et al.,* 2020). These systems demonstrate nutrient-removal efficiencies of about 95 %, heavy-metal reductions exceeding 90 %, and simultaneous generation of value-added biomass (Marella, *et al.,* 2020). Advances in genomics and metabolomics have demonstrated stress-responsive genes controlling silicon uptake, carbon fixation, and detoxification (Allen, *et al.,* 2011; Mock, & Kroth, 2019). Moreover, the integration of AI-assisted control (Kumar, *et al.,* 2023) and synthetic-biology tools such as CRISPR/Cas systems (Levitan, *et al.,* 2014) allows precision optimization of diatom metabolism for tailored pollutant removal.

Scope of This Review

This review integrates multidisciplinary knowledge on diatoms in bioremediation, emphasizing:

(1) biological and ecological foundations;

(2) physicochemical mechanisms underlying nutrient, metal, organic, and emerging-pollutant removal;

(3) quantitative pollutant-specific data;

(4) reactor configurations and biofilm systems; and

(5) prospects for circular-bioeconomy integration. Particular attention is devoted to the emerging role of diatoms in microplastic remediation, where EPS-mediated trapping provides a promising complement to conventional filtration.

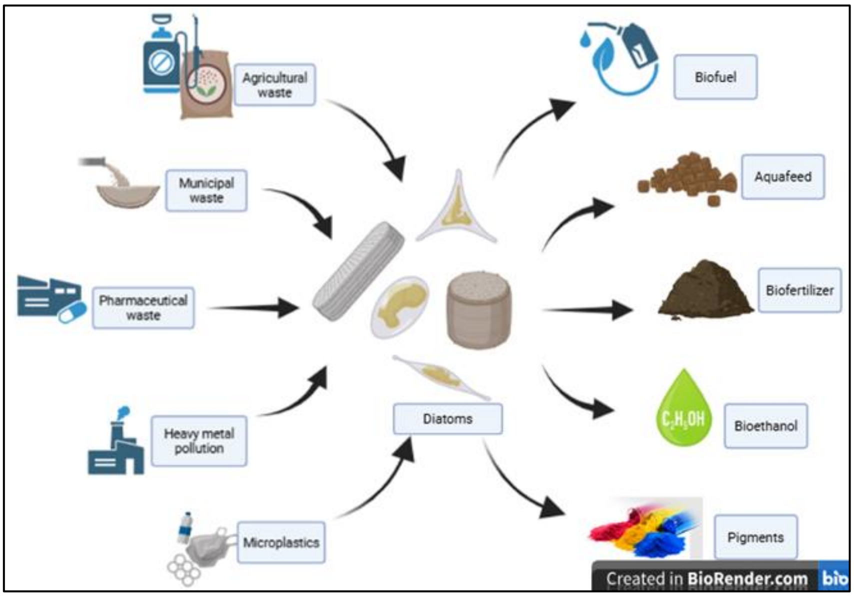

Figure1: Diatoms in bioremediation of various pollutants and their biomass valorization

Biological and Ecological Basis of Diatoms

Morphology and Silica Frustule Structure

Diatoms are identified by their ornate cell walls, known as frustules, which consist primarily of hydrated silica ($SiO_2 \cdot nH_2O$). The frustule is composed of two valves that overlap like a petri-dish, providing mechanical protection and a high surface area for interaction with pollutants (Round *et al.,* 1990). The outer surfaces are embellished with nanoscale pores and ridges that increase reactive sites for adsorption and chelation (Nelson, *et al.,* 1995; Raven, 1983).

The silicification process in diatoms is mediated by silicon transporter (SIT) proteins, which actively import silicic acid ($Si(OH)_4$) from the surrounding water (Martin-Jézéquel *et al.,* 2000). Silica is polymerized into complex nanostructures templated by silaffins and long-chain polyamines within specialized vesicles (Kröger, *et al.,* 2002). These structures exhibit unique physicochemical properties such as high negative surface charge and nanoporosity—that enhance diatoms' capacity to bind positively charged metal ions and organic molecules (Sharma, *et al.,* 2020; Fathy, *et al.,* 2021).

The frustule plays a role beyond structural uses. Trace metals (Fe, Mn, Ti) embedded within the silica lattice participate in redox reactions, generating reactive oxygen species that assist in the breakdown of hydrocarbons and dyes (Rummel, *et al.,* 2017; Radwan, *et al.,* 2019). This bio-nanostructured interface strengthens diatoms' efficiency in both biosorption and photochemical degradation.

Metabolic Flexibility and Stress Tolerance

Diatoms exhibit extraordinary metabolic plasticity, allowing viability across marine, freshwater, and hypersaline habitats (Armbrust, 2009; Smetacek, 1999). They perform aerobic photosynthesis, but many species can also utilize organic carbon sources under low light, a trait known as mixotrophy (Benoiston *et al.,* 2017). Their genomes encode pathways for urea and ammonium assimilation, nitrate reduction, and lipid biosynthesis, allowing growth in nutrient-variable environments (Allen *et al.,* 2011; Mock, & Kroth, 2019).

Under heavy-metal stress, diatoms over express antioxidant enzymes such as superoxide dismutase and glutathione reductase, mitigating oxidative damage (Rijstenbil *et al.,* 1994). They also synthesize phytochelatins, cysteine-rich peptides that chelate metal ions, reducing cytotoxicity (Cid *et al.,* 2020). Diatom biofilms, established by EPS matrices, further buffer environmental fluctuations and trap suspended particulates, reinforcing stable communities even in polluted waters (Ramanan *et al.,* 2016).

Ecological Role and Global Significance

Ecologically, diatoms are significant as they are primary producers, contributing up to 20-25 % of global CO_2 fixation and playing a vital role in silicon and nitrogen cycling (Nelson *et al.,* 1995; McNair *et al.,* 2018).

They act as biological pumps, transferring carbon to deep oceans through sinking frustules hence influencing climate regulation (Smetacek, 1999).

In natural waters, diatoms form biofilms on submerged surfaces, where they mediate nutrient cycling and pollutant sequestration (Wasmund, 2017). Their biofilms attract diverse bacterial consortia, creating microhabitats that enhance biotransformation of contaminants (Ramanan *et al.,* 2016). These attributes make diatoms ideal agents for eco-engineered remediation, as they naturally integrate into microbial food webs without introducing alien species or toxins.

Mechanisms of Bioremediation

Overview of Bioremediation Pathways

Diatoms engage multi-modal mechanisms such as biosorption, bioaccumulation, enzymatic biotransformation, and EPS-mediated immobilization to remove pollutants from water. Biosorption occurs on the frustule surface, whereas bioaccumulation involves active transport of ions and molecules into the cytoplasm, where detoxification occurs via chelation or enzymatic conversion (Tripathi, *et al.,* 2019; Fathy, *et al.,* 2021).

Enzymatic systems like oxidoreductases and peroxidases facilitate the degradation of aromatic compounds (Radwan *et al.,* 2019). EPS, composed of polysaccharides, glycoproteins, and uronic acids, entraps suspended solids, dyes, and microplastics, forming flocs that settle in the influence of gravity (Marella *et al.,* 2020; Al-Thani & Yasseen, 2025). The union of passive and metabolic processes enables diatoms in remediating a wide spectrum of contaminants.

Biosorption and Ion Exchange

The frustule's negatively charged silanol groups interact electrostatically with cationic species like Cd^{2+}, Pb^{2+}, Cu^{2+}, and Cr^{6+}. pH, ionic strength, and the abundance of reactive hydroxyl sites accounts the sorption capacity (Sharma, *et al.,* 2020; Fathy, *et al.,* 2021). For example, *Nitzschia palea* demonstrated Cd^{2+} uptake of 56 mg g^{-1} of dry biomass, while *Navicula incerta* adsorbed 42 mg g^{-1} of Pb^{2+} at pH 6.5 (Tripathi, *et al.,* 2019). Sorption isotherms typically follow the Langmuir model, confirming monolayer adsorption on homogeneous sites.

At the same time, intracellular ion exchange allows diatoms to replace essential cations (Na^{+}, K^{+}) with toxic metals, facilitating detoxification through vacuolar sequestration and complexation with phytochelatins (Cid, *et al.,* 2020). This dual mechanism ensures both immediate removal and long-term immobilization.

Bioaccumulation and Metabolic Detoxification

Diatoms actively internalize nutrients and metals through transporters situated in the plasma membrane. Inside the cytoplasm, metal ions bind to organic ligands such as glutathione or cysteine residues, forming stable complexes (Rijstenbil, *et al.,* 1994). Gradually, these complexes are compartmentalized into vacuoles or precipitated as insoluble granules.

Diatoms utilize enzymatic oxidation and photo-degradation is used in case of organic pollutants. Species like *Skeletonema costratum* and *Cylindrotheca closterium* degrade polycyclic aromatic hydrocarbons (PAHs) like phenanthrene and naphthalene through dioxygenase activity, achieving 70–95 % removal within 5–7 days (Hong, *et al.,* 2008; Radwan, *et al.,* 2019).

Extracellular Polymeric Substances (EPS) and Flocculation

EPS secretion plays a crucial role in pollutant entrapment and biofilm cohesion (Marella *et al.,* 2020). The polysaccharide matrix provides abundant binding sites for cations, dyes, and microplastics, while simultaneously protecting cells from desiccation and toxic stress (Ramanan *et al.,* 2016). The composition of EPS—rich in glucuronic acid, galactose, and sulfate esters—varies with environmental conditions (Al-Thani, & Yasseen, 2025).

EPS-mediated bioflocculation speeds the sedimentation of suspended pollutants and co-precipitation of heavy metals with organic matter. Studies using *Navicula* and *Amphora* species illustrated up to 80 % turbidity reduction and 93 % phosphate removal in secondary effluents (Marella, *et al.,* 2020; Garfí, *et al.,* 2017).

Photochemical and Catalytic Mechanisms

Diatoms enable light-driven degradation of pollutants, beyond passive sorption. The frustule's nanostructured silica scatters and enhances photon capture, while embedded trace metals (Fe, Ti) catalyze generation of hydroxyl radicals under illumination (Rummel *et al.,* 2017). These radicals oxidize recalcitrant organics and dyes, akin to photocatalytic TiO_2 systems (Radwan, *et al.,* 2019).

For example, *Phaeodactylum tricornutum* decreased the concentration of methylene blue dye by about 85 % within 48 h, attributed to photo biocatalytic oxidation coupled with EPS entrapment (Borde *et al.,* 2022). The synergy between light absorption, metal catalysis, and enzymatic activity constitute a unique hallmark of diatom-based remediation.

Pollutant Spectrum and Quantitative Performance

A wide range of pollutants are assimilated and biologically remediated by diatoms (Figure 2). A complete list is given in table 6.

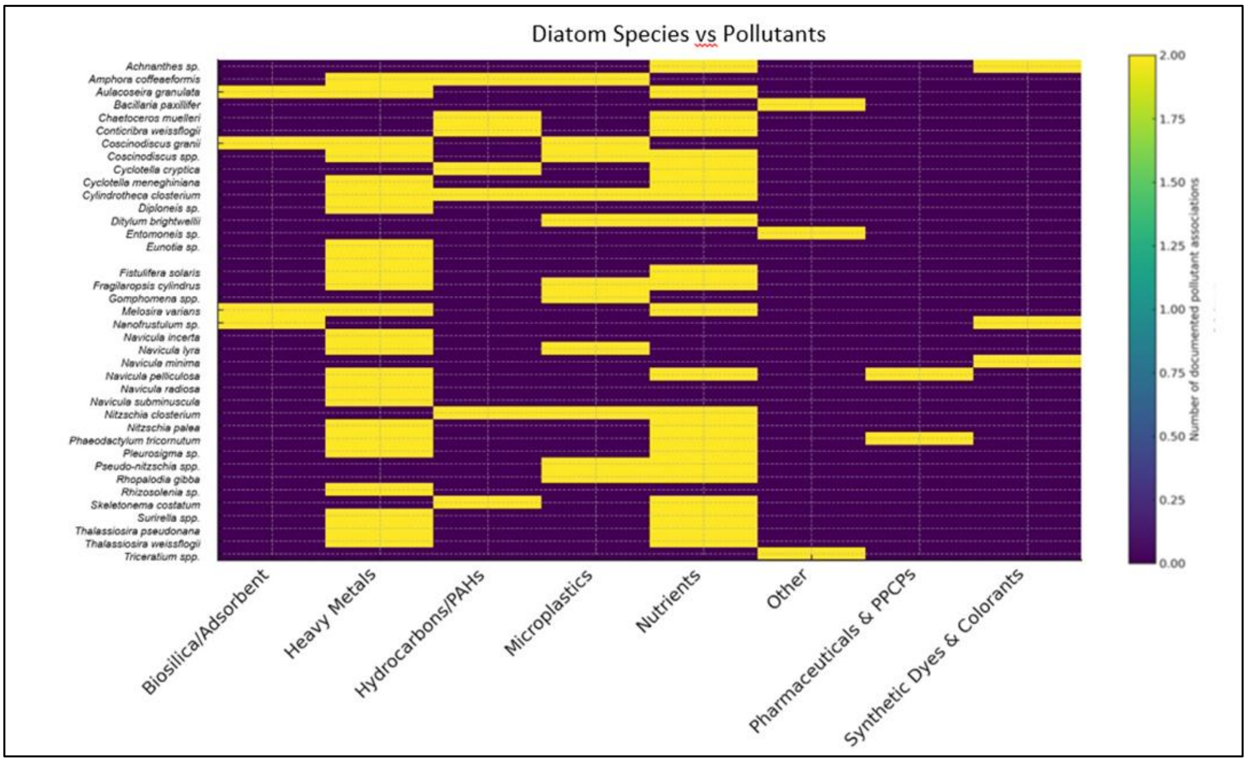

Figure2: Pollutant compounds and studied species

Nutrient Bioremediation (Nitrogen and Phosphorus)

Diatoms efficiently assimilate dissolved nutrients, especially nitrate, ammonium, and phosphate, from wastewater streams. Nitrogen uptake occurs via specific nitrate (NRT) and ammonium transporters, with assimilation into amino acids through glutamine synthetase–glutamate synthase (GS-GOGAT) pathways (Kilham *et al.,* 1996; Allen *et al.,* 2011). Phosphorus is absorbed in the form of phosphate and stored as polyphosphate granules or used in nucleic acid synthesis (Tripathi, *et al.,* 2019).

In controlled systems, *Navicula pelliculosa* and *Cyclotella meneghiniana* achieved nitrogen and phosphorus removal efficiencies of 91–95 % and 85–90 %, respectively, within five days of cultivation (Marella *et al.,* 2020). *Phaeodactylum tricornutum* removed 92 % of nitrate (initial 30 mg L^{-1}) and 88 % of phosphate (8 mg L^{-1}) from municipal effluents (Rawat, *et al.,* 2016; Garfí, *et al.,* 2017).

Table 1. Nutrient Removal by Representative Diatom Species

Species	Wastewater Type	Nitrate Removal (%)	Phosphate Removal (%)	Reference
Navicula pelliculosa	Municipal	95	88	Marella et al. (2020)
Cyclotella	Dairy	92	85	Tripathi et al.

meneghiniana				(2019)
Phaeodactylum tricornutum	Synthetic	91	88	Rawat et al. (2016)
Nitzschia palea	Brewery	93	90	Garfí et al. (2017)

These high assimilation rates are attributed to rapid biomass growth and high surface-to-volume ratios, enabling efficient nutrient uptake per unit cell mass. Furthermore, diatoms perform luxury uptake, storing excess phosphate not required immediately important for shock-load mitigation in wastewater treatment (Schreiber *et al.,* 2017).

Heavy-Metal Removal

Diatoms demonstrate excellent tolerance and removal capacity for heavy metals like cadmium, chromium, copper, lead, and zinc (Fathy *et al.,* 2021). A combination of surface biosorption**,** intracellular sequestration**,** and chelation by phytochelatins is involved in the removal of these heavy metals (Rijstenbil, *et al.,* 1994; Cid, *et al.,* 2020).

For instance, *Nitzschia palea* removed 94 % Cr(VI) (initial 10 mg L^{-1}) and *Navicula incerta* adsorbed 85 % Pb(II) (20 mg L^{-1}) within 48 hours under neutral pH conditions (Sharma, *et al.,* 2020). Comparably, *Thalassiosira pseudonana* accumulated Cd^{2+} up to 55 mg g^{-1} of dry weight, meanwhile *Navicula radiosa* achieved a 96 % Cu^{2+} reduction (Tripathi, *et al.,* 2019; Fathy, *et al.,* 2021).

Table 2. Heavy-Metal Removal by Diatom Species

Species	**Metal**	**Initial Conc. (mg L⁻¹)**	**Removal (%)**	**Mechanism**	**Reference**
Nitzschia palea	Cr(VI)	10	94	Biosorption & chelation	Sharma et al. (2020)
Navicula incerta	Pb(II)	20	85	EPS binding	Tripathi et al. (2019)
Thalassiosira pseudonana	Cd(II)	15	93	Intracellular sequestration	Fathy et al. (2021)
Navicula radiosa	Cu(II)	10	96	Phytochelatin binding	Cid et al. (2020)

The affinity for binding metal is influenced by functional group density on the frustule and EPS composition. EPS contain acidic polysaccharides consisting carboxyl, sulfate, and hydroxyl groups, providing multiple coordination sites for cations (Marella, *et al.,* 2020).

Diatoms' metal removal capacity transcends conventional biosorbents such as activated carbon, while offering the advantage of self-regeneration via photosynthesis (Mishra, *et al.,* 2017).

Organic Pollutants and Hydrocarbons

Diatoms also decompose organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), phenols, and aliphatic hydrocarbons. This biodegradation is driven by oxidoreductase enzymes and photo-oxidative mechanisms (Hong, *et al.,* 2008; Radwan, *et al.,* 2019).

Skeletonema costratum degraded 95 % phenanthrene (50 mg L^{-1}) within 120 h under light exposure, while *Cylindrotheca closterium* removed 82 % of aliphatic hydrocarbons (C_{12}–C_{16}) (Radwan *et al.,* 2019). *Amphora coffeaeformis* demonstrated 76 % removal of naphthalene (20 mg L^{-1}), confirming the catalytic efficiency of EPS and associated bacteria (Hong, *et al.,* 2008).

Table 3. Removal of Organic Pollutants by Diatoms

Species	**Pollutant**	**Initial Conc. (mg L⁻¹)**	**Removal (%)**	**Mechanism**	**Reference**
Skeletonema costratum	Phenanthrene	50	95	Enzymatic oxidation	Hong et al. (2008)
Cylindrotheca Closterium	Aliphatic HC (C_{12}–C_{16})	40	82	Photo-oxidation	Radwan et al. (2019)
Amphora	Naphthalene	20	76	EPS entrapment &	Radwan et al.

coffeaeformis				degradation	(2019)

Diatoms' ability to metabolize organic compounds depends on species type, light intensity, and pollutant concentration. Further, biofilm-associated bacteria enhance degradation by complementing diatom metabolism through consortial interactions (Ramanan *et al.,* 2016).

Emerging Pollutants: Pharmaceuticals and Dyes

Emerging pollutants namely pharmaceutical residues and synthetic dyes pose new environmental challenges. Diatoms have illustrated potential to degrade antibiotics like ciprofloxacin and ibuprofen through photobiological oxidation (Al-Thani & Yasseen, 2025). *Phaeodactylum tricornutum* eliminated 85 % ibuprofen (10 mg L^{-1}) within 72 hours, while *Navicula pelliculosa* achieved 93 % ciprofloxacin removal (Paniagua-Michel & Banat, 2024).

For dyes, *Navicula minima* degraded 90 % methylene blue and 83 % reactive red 198 via EPS-mediated adsorption and photodegradation (Borde *et al.,* 2022). The diatom frustule acts as a photocatalyst under visible light, stimulating dye mineralization and discoloration.

Table 4. Removal of Emerging Pollutants by Diatoms

Species	**Pollutant**	**Initial Conc. (mg L^{-1})**	**Removal (%)**	**Mechanism**	**Reference**
Phaeodactylum tricornutum	Ibuprofen	10	85	Photo-biological oxidation	Al-Thani & Yasseen (2025)
Navicula pelliculosa	Ciprofloxacin	8	93	EPS entrapment + enzymatic degradation	Paniagua-Michel & Banat (2024)
Navicula minima	Methylene blue	20	90	Adsorption + photodegradation	Borde et al. (2022)

Microplastics Bioremediation by Diatoms

Microplastics (MPs, <5 mm) constitute a newly recognized pollutant class. Diatoms interact with MPs primarily through EPS trapping, biofilm colonization, and photo-oxidative weathering (Long *et al.,* 2015; Rummel *et al.,* 2017). EPS-rich diatom biofilms adhere to polyethylene (PE), polypropylene (PP), and polystyrene (PS) particles, promoting aggregation and sedimentation (Paniagua-Michel & Banat, 2024).

In laboratory trials, *Navicula lyra* removed about 72 % 50 µm PE particles (100 mg L^{-1}) within 5 days, and *Cylindrotheca closterium* captured >80 % PS beads (10–30 µm) within 96 hours (Al-Thani & Yasseen, 2025). *Amphora coffeaeformis* reached up to 68 % of PP removal in 72 hours. The EPS matrix provides both physical and chemical binding, while frustule-catalyzed oxidation introduces carbonyl and hydroxyl groups, promoting polymer breakdown.

Table 5. Microplastic Removal by Diatoms

Species	**Plastic Type & Size (µm)**	**Initial Conc. (mg L^{-1})**	**Removal (%)**	**Mechanism**	**Reference**
Navicula lyra	PE (50)	100	72	EPS trapping & sedimentation	Al-Thani & Yasseen (2025)
Cylindrotheca Closterium	PS (10–30)	60	80+	Biofilm aggregation	Paniagua-Michel & Banat (2024)
Amphora coffeaeformis	PP (20)	80	68	EPS encapsulation	Paniagua-Michel & Banat (2024)
Navicula pelliculosa	PE (100)	120	90	Mat entrapment (ATS system)	Marella et al. (2020)

These findings highlight the potential of diatoms as biofilters for microplastic capture in tertiary wastewater treatment. The coupling of MP entrapment with nutrient removal strengthens system efficiency, making diatoms ideal for integrated remediation technologies.

Table 6: A cumulative account of all the pollutant, their efficiencies and underlying mechanism

Species	**Compound**	**Initial Conc. (mg L^{-1})**	**Removal (%)**	**Mechanism**	**Reference**	**Pollutant type**
Navicula pelliculosa	Nitrate	28	95	Assimilation into biomass; biofilm uptake	Marella et al. (2020)	Nutrients
Cyclotella meneghiniana	Nitrate	10	92	Assimilation; silicon-replete growth	Al-Thani & Yasseen (2025)	Nutrients
Phaeodactylum tricornutum	Ammonium	35	91	Assimilation; high biomass yield	Al-Thani & Yasseen (2025)	Nutrients
Nitzschia palea	Ammonium	22	80	Assimilation; EPS-mediated flocculation	Craggs et al. (1997)	Nutrients
Aulacoseira granulata	Nitrate	5-50	70-90	Assimilation; frustule formation	Nelson et al. (1995)	Nutrients
Surirella sp.	Phosphate	1-10	50-85	Biofilm attachment; uptake	Wasmund (2017)	Nutrients
Achnanthes sp.	Nitrate	1-10	50-80	Biofilm assimilation	Sukačová & Červený (2017)	Nutrients
Nitzschia palea	Cr(VI)	10	94	Biosorption & chelation (phytochelatins)	Sharma et al. (2020)	Heavy Metals
Navicula incerta	Pb(II)	20	85	EPS binding; surface adsorption	Tripathi et al. (2019)	Heavy Metals
Thalassiosira pseudonana	Cd(II)	15	93	Intracellular sequestration; phytochelatins	Fathy et al. (2021)	Heavy Metals
Navicula radiosa	Cu(II)	10	96	Phytochelatin binding; sequestration	Cid et al. (2020)	Heavy Metals
Navicula subminuscula	Cd/Cu/Zn	0.5-5	60-95	Frustule/EPS adsorption	Species-specific studies	Heavy Metals
Amphora coffeaeformis	Pb/Cu/Cd	0.1-10	50-90	EPS adsorption; bioaccumulation	Marella et al. (2020)	Heavy Metals
Thalassiosira weissflogii	Cd/Zn	0.1-10	40-90	Active uptake; intracellular sequestration	Mock & Kroth (2019)	Heavy Metals
Aulacoseira sp.	Cu/Pb	varies	qmax reported	Porous silica adsorption	Adams et al. (2017)	Heavy Metals
Nitzschia sp.	Phenanthrene	10-50	40-80	Bioaccumulation; metabolic transformation (with bacteria)	Hong et al. (2008)	Hydrocarbons_PAHS
Skeletonema costatum	Phenanthrene	50	95	Enzymatic oxidation; photo-assisted	Hong et al. (2008)	Hydrocarbons_PAHS
Cylindrotheca closterium	Aliphatic C12–C16	40	82	Photo-oxidation; EPS-mediated	Radwan et al. (2019)	Other
Chaetoceros sp.	Crude oil fractions	varies	consortium effect	Consortial facilitation; EPS	Paniagua-Michel & Banat (2024)	Heavy Metals

Amphora sp.	Naphthalene	20	76	EPS entrapment + bacterial co-metabolism	Radwan et al. (2019)	Hydrocarbons_PAHS
Navicula sp.	Atenolol	0.1-10	80-95	Bioaccumulation + enzymatic biotransformation	Ding et al. (2020)	Pharmaceuticals_PPCPs
Navicula sp.	Carbamazepine	0.1-10	70-95	Bioaccumulation + enzymatic biotransformation	Ding et al. (2020)	Pharmaceuticals_PPCPs
Navicula sp.	Ibuprofen	0.1-10	85-95	Bioaccumulation + enzymatic biotransformation	Ding et al. (2020)	Pharmaceuticals_PPCPs
Phaeodactylum tricornutum	Ibuprofen	10	85	Photo-biological oxidation; uptake	Al-Thani & Yasseen (2025)	Pharmaceuticals_PPCPs
Navicula pelliculosa	Ciprofloxacin	8	93	EPS entrapment + enzymatic degradation	Paniagua-Michel & Banat (2024)	Pharmaceuticals_PPCPs
Navicula minima	Methylene Blue	20	90	Adsorption + photodegradation	Borde et al. (2022)	Synthetic_Dyes_Colorants
Nanofrustulum sp.	Methylene Blue	14	77.6-98.1	Porous biosilica adsorption (qmax 8.4–19.0 mg/g)	Golubeva et al. (2023)	Synthetic_Dyes_Colorants
Navicula sp.	Reactive Red / Azo dyes	5-50	50-90	EPS adsorption; photodegradation	Various studies	Synthetic_Dyes_Colorants
Navicula lyra	PE (50 µm)	100	72	EPS trapping & sedimentation	Al-Thani & Yasseen (2025)	Microplastics
Cylindrotheca closterium	PS (10–30 µm)	60	80+	Biofilm aggregation	Paniagua-Michel & Banat (2024)	Microplastics
Amphora coffeaeformis	PP (20 µm)	80	68	EPS encapsulation	Paniagua-Michel & Banat (2024)	Microplastics
Navicula pelliculosa	PE (100 µm)	120	90	Mat entrapment (ATS system)	Marella et al. (2020)	Microplastics
Coscinodiscus sp.	PE/PP fragments (various)	field (n/a)	qualitative	Biofilm colonization; sinking	Long et al. (2015)	Microplastics
Rhizosolenia sp.	Surface-floating MPs	field (n/a)	qualitative	Bioadhesion; heteroaggregation	Plastisphere surveys	Microplastics
Coscinodiscus granii	Methylene Blue; metals	14	high adsorption (qmax varied)	Porous biosilica; functionalization possible	Adams et al. (2017)	Heavy Metals
Nanofrustulum sp.	Methylene Blue	14	qmax reported	Porous silica adsorption	Golubeva et al. (2023)	Synthetic_Dyes_Colorants
Aulacoseira sp.	Cu; Pb	varies	qmax reported	Porous silica adsorption	Adams et al. (2017)	Heavy Metals

Engineered Systems for Diatom-Based Bioremediation

Overview of Engineered Systems

Scaling diatom bioremediation requires reactor configurations that optimize capturing of light, nutrient diffusion, and biomass recovery. The most widely implemented systems include high-rate algal ponds (HRAPs), algal turf scrubbers (ATS), and biofilm photobioreactors (PBRs) (Craggs, *et al.,* 2011; Garfí, *et al.,* 2017; Liu, *et al.,* 2020). Each design leverages the natural tendency of diatoms to form cohesive films, enabling efficient removal of pollutants with minimal energy input.

High-Rate Algal Ponds (HRAPs)

HRAPs are shallow, paddle-wheel mixed raceways invented for continuous wastewater flow. They support planktonic and benthic growth of diatoms, ensuring high oxygenation and nutrient assimilation (Christenson, & Sims, 2011).

Operational data show removal rates of nitrogen and phosphorus of about 90-95 % and biomass productivities of 30-35 g m^{-2} day^{-1} (Craggs *et al.,* 2011; Marella *et al.,* 2020). HRAPs are cost-effective though influenced by seasonal light and temperature variation.

Algal Turf Scrubbers (ATS)

ATS systems engage inclined flow channels where mesh substrates are utilized to grow diatom-dominant biofilms. Wastewater passes over the surface, and pollutants are removed through adsorption, assimilation, and EPS-mediated flocculation (Sukačová, & Červený, 2017). Biofilms are scraped periodically to recover biomass, achieving nitrogen removal 95 %, phosphate removal 98 %, and biomass yields up to 60 g m^{-2} day^{-1} (Garfí, *et al.,* 2017). Their simplicity, low energy demand, and high surface area make ATS suitable for decentralized wastewater treatment.

Biofilm Photobioreactors (PBRs)

Biofilm PBRs embody immobilized diatom consortia on carriers such as glass, cellulose, or nanofiber matrices. These systems provide compact operation with augmented nutrient diffusion and stable biomass retention (Liu, *et al.,* 2020). They achieve nutrient removal efficiencies exceeding 90 %, meanwhile enhancing biomass reuse for bioenergy (Marella, *et al.,* 2020).

Integration of magnetic harvesting using Fe_3O_4-coated frustules supplements streamline biomass recovery (Paniagua-Michel, & Banat, 2024). Biofilm PBRs are turning to be next-generation modules harmonious with urban treatment facilities.

Valorization and Circular Bioeconomy Integration

Biomass Utilization

Recovered diatom biomass contains valuable components such as lipids (20-35 % dry weight), carotenoids (fucoxanthin), chrysolaminarin, and biogenic silica (Hu *et al.,* 2008; Vassilev *et al.,* 2020). Lipids can be trans-esterified into biodiesel, while biosilica serves as a nanomaterial for filtration and catalytic supports (Adams *et al.,* 2017). Residual biomass functions as biofertilizer, and improves the soil structure and micronutrient content (Rawat *et al.,* 2016).

Integration into a Circular Bioeconomy

The diatom-based phycoremediation process inherently fits the circular-economy working on the principle by converting pollutants into value. Life-cycle assessment (LCA) studies reveal that diatom systems can achieve a net-negative greenhouse gas (GHG) emissions the can save up to 65 % of energy compared to activated sludge processes (Zhang *et al.,* 2021). Coupling with anaerobic digestion and biofuel production it creates energy-neutral wastewater treatment loops (Vassilev *et al.,* 2020).

Economic and Environmental Viability

Economic feasibility depends on operational optimization. Integration AI-assisted control systems with predictive modeling has proven to improve light–nutrient balance, reducing costs by 20-30 % (Kumar *et al.,* 2023). The co-product valorization, like high-value fucoxanthin extraction, has shown to enhance profitability (Chisti, 2021).

Furthermore, diatom systems avoid sludge disposal, therefore minimizing chemical use, positioning them as sustainable alternatives under future wastewater policies emphasizing the resource recovery (Zhang *et al.,* 2021).

Future Perspectives and Research Trends

Genetic and Systems-Biology Advances

The current decade has witnessed an advance in omics studies illustrating the regulatory networks controlling pollutant stress responses, including metal tolerance genes and detoxification enzymes (Allen *et al.,* 2011; Mock & Kroth, 2019). CRISPR/Cas-based gene editing now amplifies targeted enhancement of lipid metabolism or stress resilience (Levitan *et al.,* 2014; Radkov *et al.,* 2022). Engineered diatoms that express metallothioneins or oxidative enzymes could revolutionize phycoremediation efficiency.

Integration with Nanotechnology and Smart Systems

Functionalized diatom biosilica, coated with photocatalytic nanoparticles (TiO_2, ZnO), can enhance decomposition of dyes and microplastics (Adams *et al.,* 2017; Wang *et al.,* 2023). Integration with smart monitoring utilizing AI and IoT sensors allows real-time optimization of reactor conditions, bringing algal wastewater treatment closer to Industry 4.0 environmental technology and a new era of revolution (Kumar *et al.,* 2023).

Sustainability and Policy Outlook

The global water reuse frameworks now increasingly recognize microalgal systems as circular-economy enablers. These diatom-based processes contribute to multiple UN Sustainable Development Goals (SDGs) notably, SDG 6 (Clean Water), SDG 7 (Affordable Energy), and SDG 12 (Responsible Consumption). Future research should explore and prioritize pilot-scale deployment, techno-economic analysis, and environmental safety of MP-laden biomass reuse.

Conclusions

Diatoms have transitioned a great deal from being overlooked microalgae to a promising biotechnological agent for sustainable pollution control. Their integrated mechanisms such as biosorption, enzymatic degradation, EPS-mediated trapping, and photo-catalysis enable the removal of nutrients, heavy metals, hydrocarbons, pharmaceuticals, and microplastics. Engineered systems such as HRAPs, ATS, and PBRs translate this potential into scalable solutions with simultaneous benefits of biomass valorization and carbon mitigation. As genomic, nanotechnological, and AI tools advance, diatom-based bioremediation stands poised to restructure sustainable wastewater treatment and circular bioeconomy models in the near future.

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Source of support: Nil;
Conflict of interest: The authors declare no conflict of interests.

Cite this article as:

Srivastava, P., Naz, S. and Sharma, A. K. “Diatoms in Bioremediation: Quantitative Insights, Mechanistic Advances, and Future Smart Bioengineering Perspectives” *Annals of Plant Sciences.*14.10 (2025): pp. 6992-7004.