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Exploring Role of Bioactive Molecules produced by Diatoms in Heavy Metal Alleviation

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Abstract- Heavy metal pollution poses a persistent threat to aquatic ecosystems, necessitating innovative and sustainable remediation strategies. Diatoms which are single-celled, photosynthetic microalgae, have appeared as optimistic candidates for heavy metal detoxification. This work explores the ecological risks associated with heavy metals namely cadmium (Cd), lead (Pb), mercury (Hg), zinc (Zn), copper (Cu) and chromium (Cr), and examines the cellular stress responses they trigger. It highlights the distinctive biological architecture of diatoms, which confer resilience and biosorptive capacity. The study delves into the bioactive molecules produced by diatoms, that play pivotal roles in metal chelation and oxidative stress mitigation. By bridging ecological understanding with applied biotechnology, this work underscores the multifaceted potential of diatoms in environmental remediation and commercial innovation.

Keywords: Sustainable Remediation, Detoxification, Ecological Risks, Biosorptive Capacity, Bioactive Molecules.

I. INTRODUCTION

1.Overview of Heavy Metal Pollution and Ecological Risks - Access to clean water is a fundamental necessity for all life forms across the globe. Nevertheless, rapid technological progress and modern human activities are increasingly threatening aquatic ecosystems (Ganeshkumar et al., 2018). Over the past century, industrialization has accelerated dramatically, leading to the unsustainable exploitation of natural resources and intensifying global environmental pollution (Gautam et al., 2016). A wide array of contaminants encompassing non-organic ions, carbon compounds, metalorganic substances, radiative materials, gaseous emissions, and microparticles, have acutely degraded environmental quality (Walker et al., 2012).

The term "heavy metals" now typically refers to metallic elements and metalloids that constitute substantial toxicity peril to both environment and human well-being (L. K. Wang et al., 2009; Tchounwou et al., 2012; Briffa et al., 2020). These substances are ordinarily characterized by a density exceeding 5 g/cm^3 and are frequently encountered in daily life (Briffa et al., 2020). Anthropogenic activities are the principal drivers of heavy metal pollution, with major contributors involving mining, smelting, metal-dependent industries, and the leaching of metals from landfills, waste sites, animal excreta, agricultural runoff, vehicular emissions, and road construction. Agricultural practices also impart remarkably to heavy metal poisoning through the extensive use of herbicides, biocides, and chemical fertilizers.

Moreover, natural phenomena such as volcanic explosion, metal oxidation, vaporization from soil and water, sediment disturbance, erosion, and topographical disintegration furthermore aggravate heavy metal dispersion (Shallari et al., 1998; Herawati et al., 2000; He et al., 2005; Tchounwou et al., 2012; Walker et al., 2012; Gautam et al., 2016; Masindi & Muedi, 2018).

The escalating use of heavy metals has directed to a marked increase in their presence across terrestrial and oceanic ecosystems (Gautam et al., 2016). Once ingested or inhaled, these metals tend to bioaccumulate within biological systems, ensuing in various physiological and pathological disorders (L. K. Wang et al., 2009; Tchounwou et al., 2012; Gautam et al., 2016; Briffa et al., 2020). The capability of heavy metals to persist, accumulate, and potential to biomagnify through aquatic food webs make them particularly hazardous to living organisms (Ouyang et al., 2018).

II. PHYSIOLOGICAL ADVANTAGES OF DIATOMS IN CONTRAST WITH OTHER ALGAE

Diatoms are single-celled, eukaryotic planktonic algae habitually found in aqueous ecosystems, either as free-floating cells or adhered to surfaces in diverse morphological arrangements such as colonies, filaments, ribbons (e.g., Fragilaria), fans (Meridion), zigzags (Tabellaria), or star-like forms (Asterionella). With around 200 genera and over 100,000 species, they represent a vast and ecologically significant group. Taxonomically, diatoms pertain to the phylum Heterokontophyta, class Bacillariophyceae, and division Bacillariophyta. They are categorized into centric forms (Coscinodiscophyceae), pennate forms without raphe (Fragilariophyceae), and pennate forms with raphe (Bacillariophyceae). These golden-brown algae displayed incredibly enhanced photochemical efficiency and are rich in biologically active substances and beneficial pigments (Fu et al., 2017).

The evolutionary trajectory and genomic architecture of diatoms are distinct, granting them with specialized metabolic capabilities (Datta et al., 2019; Morozov & Galachyants, 2019). Genomic analyses have positioned diatoms as promising candidates for genetic engineering and synthetic biology applications, enabling their use in developing micro- and nano-scale devices, water purification systems, biosensors, solar technologies, and drug delivery platforms due to their superior optical, electrical, mechanical, and biocompatible properties (Uthappa et al., 2018).

Diatoms showed rapid growth, with division rates reaching 2–4 cycles per day. Their cell walls, composed of biosilica, form intricate three-dimensional structures called frustules. These frustules act as pH buffering systems, enhancing carbonic anhydrase activity at the cell membrane and facilitating the conversion of bicarbonate into carbon dioxide (CO_2) (Marella et al., 2020). Compared to other algal groups, diatoms demonstrate superior carbon fixation capacity in field as well as in experimental conditions (Bach et al., 2019). Their photochemical reaction efficiency remains robust even under low light, with species like Phaeodactylum tricornutum outperforming green algae such as Chlorella vulgaris in biomass production under limited irradiance (Wagner et al., 2006).

A notable metabolic feature of diatoms is the existence of a functional urea cycle, absent in chlorophytes (Armbrust et al., 2004). This unique trait, along with their other physiological advantages, makes diatoms highly effective in wastewater treatment and heavy metal sequestration, reinforcing their relevance in phycoremediation strategies (Bhaskar et al., 2016). Diatoms also serve as reliable indicators of aquatic ecosystem health. They are instrumental in monitoring water characteristics across lagoons, streams, and seas (Lobo et al., 2016). In estuarine and shallow water systems, benthic diatoms dominate the algal communities. Their short life cycles and sensitivity to environmental fluctuations allow them to swiftly reflect changes in water conditions, making them valuable bioindicators (X.-W. Wang et al., 2019). Ergo, benthic diatoms are frequently utilized in pollution assessment and bioassessment programs (Lin et al., 2020). Changes in their community structure can be leveraged to recognize variants with high capability for heavy metal remediation (Marella et al., 2020).

III. DIATOM MEDIATED HEAVY METAL REMEDIATION

Phycoremediation, an algae-based approach to wastewater treatment, has been widely endorsed for the mitigation of heavy metals, insecticides, and various pollutants (Tiwari & Marella, 2019). Among algal candidates, diatoms offer distinct advantages over conventional remediation techniques due to their widespread occurrence, rapid growth, environmental adaptability, non-toxic nature, and eco-friendly profile. Their autotrophic metabolism enables low-energy remediation, rendering the system cost-effective, sustainable, reusable, and recyclable, attributes that have garnered noteworthy scientific interest globally (Sunday et al., 2018).

The bioremediation of heavy metals via diatoms typically involves a two-phase mechanism: an initial biosorption step, where metals bind to specific ligands on the cell surface, after that bioaccumulation occurred, an intracellular process mediated by non-organic molecules and enzymatic systems (Hernández-Ávila et al., 2017). Diatoms have evolved a suite of strategies to alleviate heavy metal toxicity, including biotransformation, biomineralization, biosorption, and bioaccumulation (Tiwari & Marella, 2019). Their defence arsenal further encompasses metal exclusion, decontamination pathways, modulation of metal-binding ligand synthesis, modification of surface ligands, and the generation of antioxidant compounds (Marella et al., 2020).

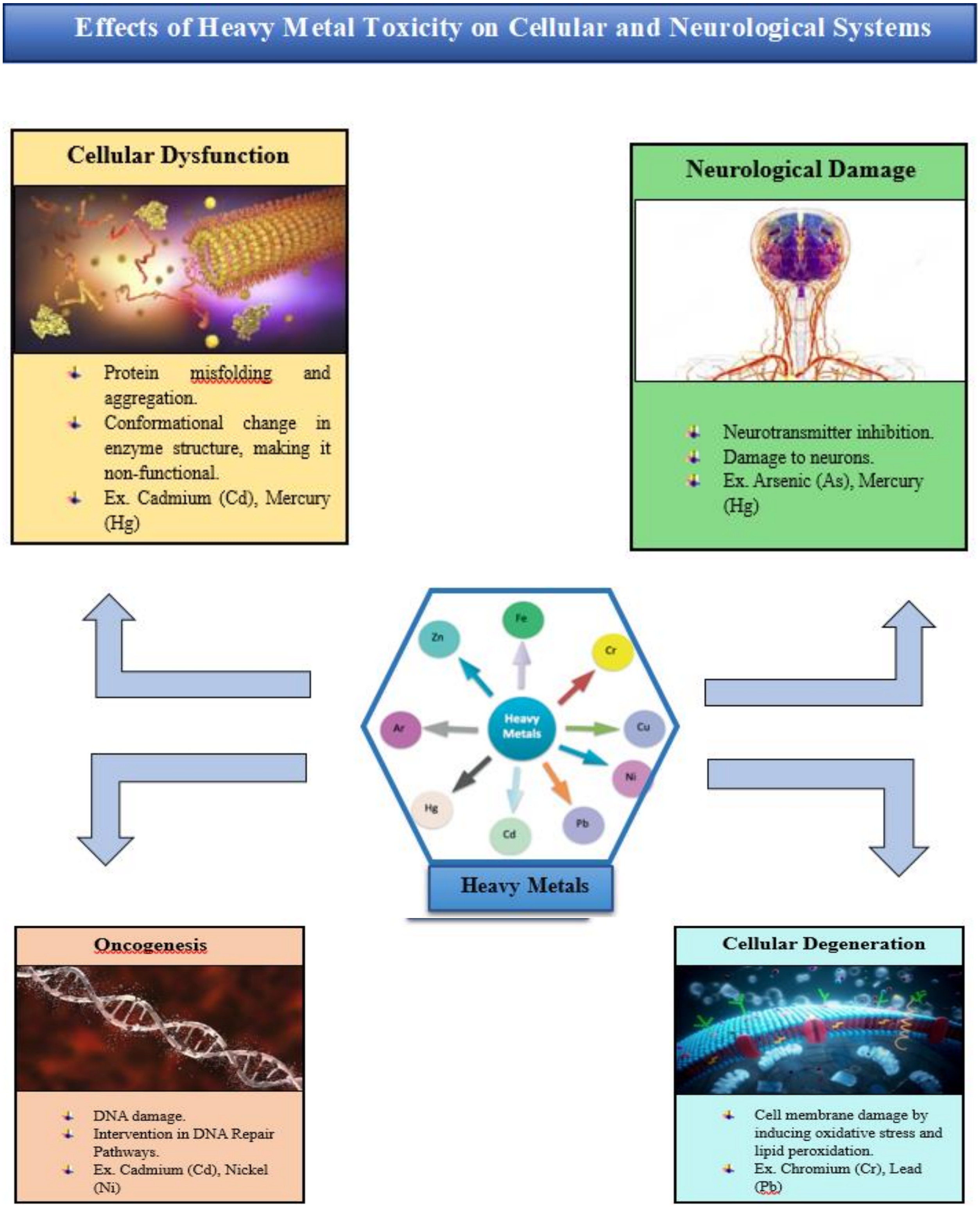
IV. HEAVY METAL TOXICITY AND CELLULAR STRESS RESPONSE

Heavy metals can enter the human body through four primary routes: intake of adulterated food, inspiration of foul air, uptake of tainted water, and dermal exposure arising from agricultural, pharmaceutical, industrial, residential, and manufacturing activities (Walker et al., 2012; Masindi & Muedi, 2018). Once internalized, these metals can disrupt various cellular structures and organelles, incorporating mitochondria, nuclei, lysosomes, cytoplasmic membranes, and enzymatic systems. Notably, metal ions have been shown to interfere with DNA and nuclear proteins, leading to genotoxic effects such as DNA damage, altered cell cycle regulation, apoptosis, and even oncogenesis (Tchounwou et al., 2012).

The cellular damage induced by heavy metals can be categorized into two types: direct and indirect. Direct damage involves structural alterations to biomolecules caused by metal interactions. Indirect damage, however, stems from the generation of reactive oxygen and nitrogen species (ROS and RNS), encompassing hydroxyl and oxygen free radicals, dihydrogen dioxide, nitrogen monoxide, and further endogenous free radicals. These heavy metals can turn on intracellular signal transduction cascades (Valko et al., 2005).Certain metals can generate reactive radicals, contributing to oxidative stress and triggering a cascade of harmful effects such as DNA fragmentation, fatty acid oxidation, and reduction of protein sulfhydryl groups. Metals such as copper, iron, cadmium, chromium, nickel, mercury, and vanadium are particularly implicated in these oxidative reactions (Briffa et al., 2020). Fig. 1 provides a schematic representation of how heavy metals interfere with cellular homeostasis, culminating in cytotoxic and neurotoxic effects.

Common Heavy Metals in Aquatic Ecosystem and their Impacts - The most prevalent heavy metals detected in aqueous environments include cadmium (Cd), copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), and mercury (Hg). Cadmium compounds are extensively utilized in the plastic industry as colorants, in anticorrosive coatings for steel, and in the production of electrical cells (Mu et al., 2018). Cd also occurs inherently in mineral reserves and metal ores. It is readily absorbed by filter-feeding fish, facilitating biomagnification across trophic levels (Rizwan et al., 2019). In humans, cadmium exposure is associated with severe renal impairment and osteoporosis (Rebelo & Caldas, 2016). Copper, because of its high solubility in water, can infiltrate aquatic systems through industrial discharge and anthropogenic activities.

Acute Cu toxicity may result in gastrointestinal distress, including vomiting and abdominal pain, and in critical cases, organ dysfunction or mortality. Zinc exposure can lead to symptoms such as nausea, abdominal cramps, and internal hemorrhaging. Lead poisoning is linked to kidney dysfunction, hypertension, and neurological damage (Utomo et al., 2016). Chromium ingestion generally causes acute toxicity, manifesting as peptic ulcer, sickness, emesis, pyrexia, dysentery, dizziness, renal disorder, and hepatic injury. Chronic exposure through inhalation or repeated dermal contact may result in allergic dermatitis, eczema, gingivitis, mucosal irritation, bronchitis, hepatic and renal disorders, sinusitis, pneumonia, and even bronchogenic carcinoma. Mercury inhalation is known to provoke respiratory and ocular irritation, skin rashes, vomiting, diarrhoea, and reproductive toxicity. It discloses genotoxic properties, damaging DNA and chromosomes, and is implicated in congenital disorders such as Down syndrome (formerly referred to as Mongolism) and neurological conditions like Minamata disease Chisso-Minamata disease (Briffa et al., 2020).


Effects of Heavy Metal Toxicity on Cellular and Neurological Systems

Cellular Dysfunction

- Protein misfolding and aggregation.
- Conformational change in enzyme structure, making it non-functional.
- Ex. Cadmium (Cd), Mercury (Hg)

Neurological Damage

- Neurotransmitter inhibition.
- Damage to neurons.
- Ex. Arsenic (As), Mercury (Hg)

Heavy Metals

Oncogenesis

- DNA damage.
- Intervention in DNA Repair Pathways.
- Ex. Cadmium (Cd), Nickel (Ni)

Cellular Degeneration

- Cell membrane damage by inducing oxidative stress and lipid peroxidation.
- Ex. Chromium (Cr), Lead (Pb)

Fig. 1 Mechanistic Overview of Heavy Metal-Induced Cytotoxicity and Neurotoxicity

V. DISTINCTIVE TRAITS OF DIATOMS

Diatoms, often referred to as golden-brown algae, are omnipresent in aquatic environments and constitute a major component of the microalgae assemblage. They are accountable for approximately 40% of the total primary production in marine ecosystems (Mann & Droop, 1996; Winter & Duthie, 2000; Cavalier-Smith, 2018). Each diatom cell is encased in a highly ornate silica-based wall known as a frustule, composed of hydrated silicon dioxide. Through photosynthesis, diatoms convert solar energy into biochemical energy—a trait they share with terrestrial plants, although this autotrophic capability evolved independently in both lineages. Genomic studies reveal that diatoms possess a chimeric genome, incorporating genes from green algae, cyanobacteria, and red algae (Mal et al., 2022).

Biological Characteristics

Diatoms may exist as solitary cells or in colonies, ranging from single-celled to pluricellular forms. They can be motile or non-motile and often form periphytic colonies that are filamentous or embedded in mucilage (Graham et al., 2012). Their frustules exhibit diverse morphologies—elliptical, triangular, circular, or crescent-shaped—and may display radial (centric) or bilateral (pennate) symmetry. Secondary structural features namely spines and bristles are also common. Diatoms follow a diplontic life cycle, predominantly reproducing asexually through vegetative division, which leads to progressive size reduction. This is counterbalanced by sexual reproduction via auxospore formation, restoring the original cell size (Mal et al., 2022).

Biochemical Characteristics

The frustule is enriched with pectin and various glycans. Diatom chloroplasts are enveloped by a dual membrane and further encased by four layers of chloroplast endoplasmic reticulum. Thylakoids are arranged in triplet stacks within a single girdle lamella. Their light reaction apparatus includes chlorophyll a, c_1, and c_2, along with carotenoids such as provitamin A and luteins—fucoxanthin, diatoxanthin, and diadinoxanthin. Fucoxanthin imparts the distinguished tawny hue to the plastids. Diatoms store energy primarily as chrysolaminarin (a soluble carbohydrate in the vacuole), along with oil and volutin granules (Sims et al., 2006).

Evolutionary Characteristics

Diatoms are classified as secondary endosymbionts, possessing chloroplasts acquired from red algae, yet regulated by nuclear genomes of green algal origin (Armbrust, 2009). Exceptionally, diatoms endured the catastrophic Permian-Triassic mass extinction event, which eradicated nearly 96% of marine life, accentuating their evolutionary resilience (Mal et al., 2022).

VI. BIOACTIVE MOLECULES PRODUCED BY DIATOMS

Diatoms synthesize a variety of bioactive compounds that play pivotal roles in heavy metal remediation. Key molecules include:

Exopolysaccharides (EPS) Extracellular polymeric substances (EPS) are secreted by diatoms through mechanisms such as excretion, secretion, sorption, and cell lysis. These substances form a miscellaneous matrix predominantly consists of glycans, along with peptides, fatty acids, and organic materials. The polysaccharide-rich fraction is specifically termed exopolysaccharides (EPS). Diatom-derived EPS are increasingly studied for their multifunctional roles in aquatic ecosystems, including enhancing particle aggregation and organic carbon flux to deeper waters, providing desiccation resistance in intertidal zones, facilitating colony formation, and promoting symbiotic interactions with bacteria (Jin et al., 2018).

Metallothioneins and Phytochelatins

Metallothioneins (MTs) are low molecular mass (<10 kDa), cysteine-enrich peptides with a high affinity for metal ions such as cadmium (Cd). These proteins act as cellular defenders by forming organometallic complexes that mitigate metal toxicity. MTs are found across diverse biological taxa including animals, bacteria, plants, fungi, yeast, and microalgae. They are classified into MTI, MTII, and MTIII, with Class III MTs—known as phytochelatins, being enzyme-catalyzed thiolate peptides prevalent in plants and algal groups such as Chlorophyta, Chrysophyta, Xanthophyta, and Euglenophyta.

Phytochelatins are synthesized in the cytosol and are present both intracellularly and extracellularly. Extracellular phytochelatins bind metal ions to precipitate and sustain them on the cell membrane, preventing cellular uptake, while intracellular phytochelatins facilitate metal sequestration within organelles, thereby reducing cytotoxicity (Tripathi & Poluri, 2021).

6.3 Polyphenols - Phenolic compounds and their by-products, comprising simple phenols, flavonoids, phenylpropanoids, tannins, and lignins—contain aromatic rings and hydroxyl groups that determine their radical scavenging capacity. Although compounds including pheophytin (from chlorophytes) and phlorotannins (from phaeophyceae) are recognized for their antioxidant properties, they may not be the primary givers to the overall oxidation inhibitor potential of microalgae (Goh et al., 2010).

6.4 Organic Acids - Diatoms also produce various organic acids, entailing citrate, ethanedioic, maltonic, trans-butenedioic, lactate or milk, and apple acids. These acids chelate toxic metal ions, forming metallo-organic complexes that enhance the dissolution and leaching of metal contaminants from surfaces (Köhler et al., 2017).

VII. MECHANISMS OF HEAVY METAL ALLEVIATION

Heavy metal detoxification in microalgae, particularly diatoms, occurs via two principal pathways: extracellular biosorption and intracellular biosorption.

Extracellular Biosorption Mechanisms

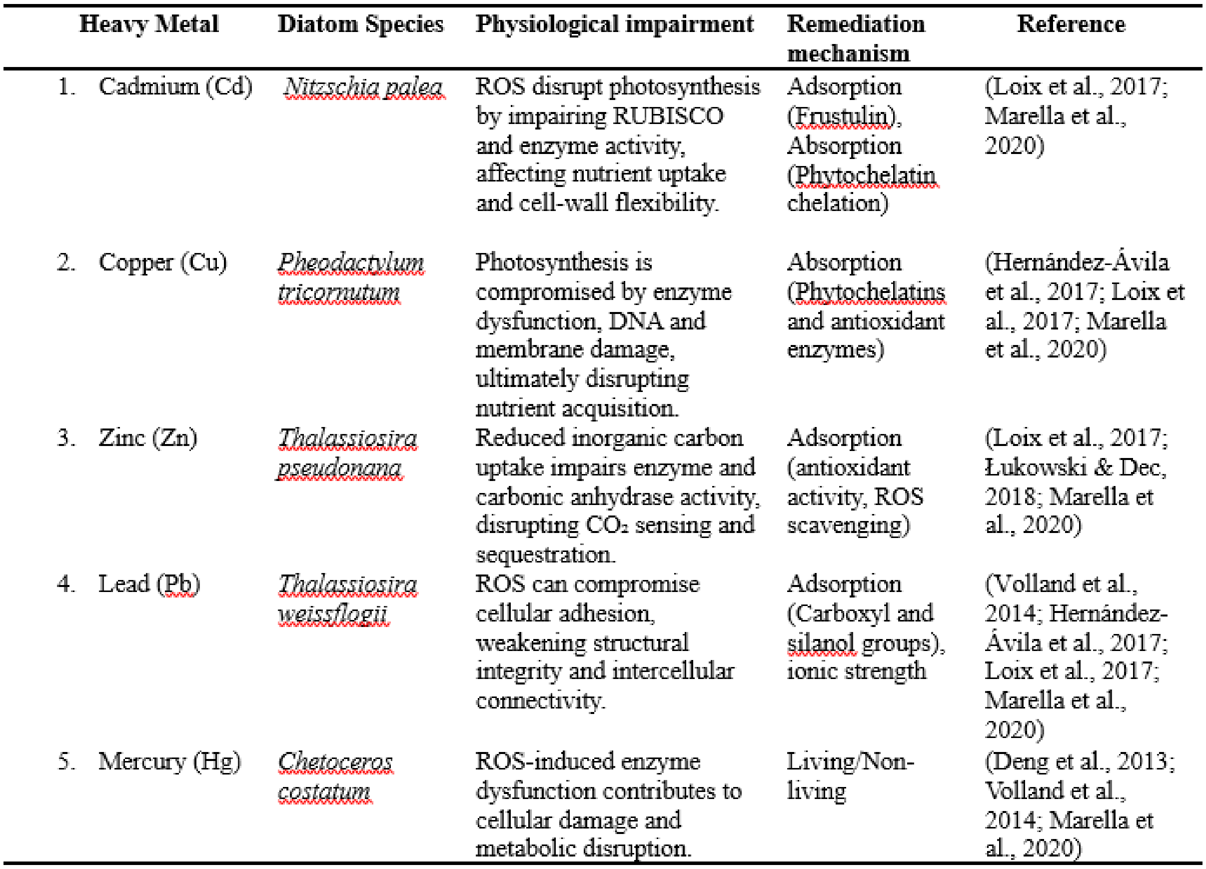
Extracellular biosorption is a physicochemical process through which heavy metals are sequestered from contaminated water, either passively—without ATP—or actively, involving ATP-dependent metabolic pathways (X.-W. Wang et al., 2019). In its non-energy requirement form, biosorption happens at the cell membrane and is governed by steadiness dynamics. Key components influencing its efficiency include pH, temperature, contact time, ion concentration, organic matter and metal concentrations, cell wall constitution, and the nature of metal ion complexation (Ding et al., 2017). This method offers several advantages: low operational costs, minimal sludge generation, and high efficacy in detoxifying trace metal concentrations, including in situ applications. The cell walls of microalgae are rich in polymers analogous to cellulose, pectins, hemicelluloses, arabinogalactan proteins, extensins, and lignins.

These walls contain functional groups—carboxyl, phosphoryl, and amine—that confer a minus charge, facilitating electrostatic attraction and binding of positively charged metal ions (Ding et al., 2017; X.-W. Wang et al., 2019). Benthic diatoms often form mutualistic biofilms with prokaryote, during which they secrete extracellular polysaccharides (EPS) that enhance metal ion adhesion to the cell membrane (Koedooder et al., 2018). The silica frustules of diatoms, composed of crystalline aluminum silicates with tetrahedral structures, enable metal complexation via two modes:

- Inner-sphere complexation, where ligands directly coordinate with the central metal ion.
- Outer-sphere complexation, where oppositely charged ions form ion pairs within a critical proximity.

Diatoms possess a diverse array of functional groups—amino (–NH_2), carboxyl (–COOH), silanol (Si–OH), aldehyde, ketone, ester, and phytochelatins—embedded in a three-dimensional micro- to nano-porous matrix. These structures modulate surface charge, metal affinity, and detoxification potential (Lane & Morel, 2000). Table 1 outlines how different diatom species respond heavy metal exposure through implying various remediation mechanisms.

Table 1 Diatom-Based Remediation of Heavy Metal Toxicity: Species-Specific Mechanisms and Physiological Impacts



	Heavy Metal	Diatom Species	Physiological impairment	Remediation mechanism	Reference
1.	Cadmium (Cd)	*Nitzschia palea*	ROS disrupt photosynthesis by impairing RUBISCO and enzyme activity, affecting nutrient uptake and cell-wall flexibility.	Adsorption (Frustulin), Absorption (Phytochelatin chelation)	(Loix et al., 2017; Marella et al., 2020)
2.	Copper (Cu)	*Pheodactylum tricornutum*	Photosynthesis is compromised by enzyme dysfunction, DNA and membrane damage, ultimately disrupting nutrient acquisition.	Absorption (Phytochelatins and antioxidant enzymes)	(Hernández-Ávila et al., 2017; Loix et al., 2017; Marella et al., 2020)
3.	Zinc (Zn)	*Thalassiosira pseudonana*	Reduced inorganic carbon uptake impairs enzyme and carbonic anhydrase activity, disrupting CO_2 sensing and sequestration.	Adsorption (antioxidant activity, ROS scavenging)	(Loix et al., 2017; Łukowski & Dec, 2018; Marella et al., 2020)
4.	Lead (Pb)	*Thalassiosira weissflogii*	ROS can compromise cellular adhesion, weakening structural integrity and intercellular connectivity.	Adsorption (Carboxyl and silanol groups), ionic strength	(Volland et al., 2014; Hernández-Ávila et al., 2017; Loix et al., 2017; Marella et al., 2020)
5.	Mercury (Hg)	*Chetoceros costatum*	ROS-induced enzyme dysfunction contributes to cellular damage and metabolic disruption.	Living/Non-living	(Deng et al., 2013; Volland et al., 2014; Marella et al., 2020)

Intracellular Biosorption Mechanisms

Intracellular biosorption is an active, energy-dependent process wherein organisms internalize heavy metals at accelerated rates. This uptake occurs alongside nutrient assimilation, contributing to pollutant removal from wastewater (Kumar et al., 2015). The process involves two phases:

- Passive uptake, characterized by rapid adsorption of metal ions onto the cell surface via adsorbate (Perales-Vela et al., 2006).
- Active uptake, involving a series of metabolic mechanisms:

a) Cell wall detoxification via complexation with exopolysaccharides and phytochelatins.

b) Energy-driven efflux pumps regulate metal ion influx based on extracellular concentration gradients.

c) Enzymatic modification of intracellular metal ions alters their oxidation states, facilitating volatilization and excretion. Methylation reduces metal reactivity, protecting sensitive intracellular sites.

d) Intracellular transport of metal ions by ligands such as polyphosphates and polychelatins, which neutralize toxicity.

e) Binding of metal-ligand complexes to cytoplasmic and intracellular membranes, neutralized heavy metals are transferred into membranes.

f) Utilization of detoxified metals by organelles for metabolic functions.

Diatoms further enhance detoxification through enzymatic processes such as dehalogenation and denitrification, contributing to their resilience in metal-polluted environments (Kumar et al., 2015; Marella et al., 2020).

VIII. FACTORS INFLUENCING HEAVY METAL REMEDIATION BY DIATOMS

The efficiency of heavy metal adsorption by diatoms is governed by multiple physicochemical and biological parameters, including metal concentration, biomass availability, temperature, pH, and ionic composition of the medium.

Metal Concentration

Initial metal concentration plays a critical role in adsorption dynamics. As the quantity of heavy metals in wastewater enhances, adsorption initially rises due to the availability of binding sites, but eventually reaches saturation. Diatom cell surfaces possess a variety of functional groups with differing affinities—low-affinity groups tend to bind metals at higher concentrations, while high-affinity groups are more effective at lower concentrations. Consequently, beyond a threshold, the overall removal efficiency may decline (Mehta & Gaur, 2005).

pH - pH significantly influences metal uptake. Studies indicate that metal adsorption by diatoms improves with increasing pH (J. Zhang et al., 2015). Optimal pH conditions vary by metal type: slightly acidic conditions favour the removal of cadmium (Cd), nickel (Ni), and zinc (Zn), whereas more acidic environments are optimal for copper (Cu) and lead (Pb) adsorption (Hernández-Ávila et al., 2017).

Biomass Concentration

The concentration and viability of biomass are crucial. Living diatom biomass, enriched with active surface ligands, demonstrates superior adsorption capabilities compared to non-living biomass, owing to its metabolic activity and dynamic surface chemistry.

Temperature

Temperature also modulates adsorption efficiency. In many cases, increased temperature enhances metal uptake, suggesting an endothermic adsorption process. For example, Chlorella vulgaris shows improved nickel adsorption at elevated temperatures. However, contrasting evidence from macroalgae such as Sargassum sp. suggests an exothermic mechanism, with cadmium (Cd^{2+}) adsorption occurring effectively at ambient temperatures (Mehta & Gaur, 2005).

Ionic Composition

The existence of competing anions and cations in the medium can hinder metal adsorption by occupying active sites or forming stable complexes. These ions may engage in inner-sphere complexation with heavy metals, thereby diminshing the availability of binding sites and weakening electrostatic interactions between metal ions and diatom surfaces (John et al., 2018).

IX. TECHNOLOGICAL ADVANCEMENTS IN WASTEWATER REMEDIATION

Wastewater treatment technologies encompass a range of physical, chemical, biological, and integrated approaches. Physical methods typically involve adsorption techniques using materials specifically activated carbon, graphene oxide, filtration systems, and flocculation agents to capture heavy metal contaminants. Chemical methods include ozonation, redox reactions, ionizing radiation, and ultraviolet (UV) treatments. While these approaches can partially remove heavy metals, they often require costly infrastructure, hazardous reagents, skilled personnel, and extended processing times, rendering them less viable for long-term, sustainable environmental management. In contrast, biologically driven technologies—particularly those mediated by diatom algae, offer a promising alternative. Diatoms facilitate both biodegradation and photodegradation of heavy metals, positioning them as key agents in phycoremediation strategies (Yan et al., 2018).

Open Pond Bioreactors

Open-pond systems with minimal aeration are commonly employed in agricultural and industrial wastewater treatment due to their low capital and operational costs and ease of maintenance. However, these systems face limitations such as susceptibility to contamination, high nutrient input requirements, and large land footprint (Cuellar-Bermudez et al., 2017).

High-Rate Algal Ponds (HRAPs)

An advanced variant of open pond systems is the raceway pond or high-rate algal pond (HRAP), which intensify treatment efficiency through a symbiotic association between diatoms and prokaryote. Diatoms perform photosynthesis, releasing oxygen that bacteria utilize to degrade heavy metal pollutants thus eliminating the need for mechanical aeration (Sawant et al., 2018).

Bubble Column Photobioreactors

These closed systems are engineered in vertical, horizontal, or helical configurations using translucent tubing to optimize exposure to natural or artificial illumination (Nwoba et al., 2019). Compared to open ponds, bubble column photobioreactors offer superior control over pH and temperature, higher volumetric productivity, efficient land use, enhanced light capture, and reduced water loss. Despite their technical advantages, the high operational costs remain a serious barrier to widespread adoption (Gouveia et al., 2016).

Algal Turf Scrubbers (ATS)

Algal biofilm-based remediation systems, commonly referred to as algal turf scrubbers, utilize a consortium of microalgae—including cholrophycean, cyanobacteria, and diatom species, to integrate nutrients and heavy metals from wastewater (Huang et al., 2013). This environmentally friendly technique is increasingly used to concentrate heavy metals into algal organic matter, facilitating downstream recovery and valorization (Adey et al., 2011).

X. COMMERCIAL APPLICATIONS OF DIATOMS AND THEIR HIGH-VALUE METABOLITES

Diatoms are increasingly recognized for their multifaceted commercial utility, spanning wastewater treatment, aquaculture, nutraceuticals, pharmaceuticals, and nanobiotechnology. Their ability to produce a wide spectrum of bioactive metabolites underpins their relevance across these sectors.

Wastewater Treatment

Diatom consortia are employed in the degradation of waste materials due to their physiological sensitivity to environmental fluctuations. Technologies such as Algal Floway (AFW), which leverage dominant pennate diatom communities, facilitate silica enrichment in untreated water bodies and enable nutrient removal in a cost-effective and sustainable manner (Marella et al., 2019).

Aquafeed

Diatoms are considered ideal feedstock in aquaculture, particularly in fisheries and hatcheries. Their rapid life cycle and high nutritional value yield substantial residual biomass post-harvest, rich in lipids, proteins, and polysaccharides, making them a invaluable resource for aquatic feed formulations (Mal et al., 2022).

Nutraceuticals

From a nutraceutical perspective, diatoms are prized for their bioactive compounds with established health benefits. Key metabolites of interest include the carotenoid fucoxanthin, the polysaccharide chrysolaminarin, and omega-3 polyunsaturated fatty acids (PUFAs) viz eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Nieri et al., 2023).

Antiviral Potency Several diatom-derived compounds exhibit promising antiviral properties and are under investigation for pharmaceutical applications (Lee et al., 2006). For example, Haslea ostrearia produces marennine, a blue pigment with demonstrated antiviral activity in laboratory settings. Additionally, naviculan—a sulfated polysaccharide from Navicula directa—has shown efficacy against herpes simplex viruses (HSV-1, HSV-2) and influenza viruses (Mal et al., 2022).

Nanobiotechnology

The intricate architecture and patterned biosilica of diatoms are harnessed in nanotechnology for the fabrication of nanomaterials such as biosilica nanoparticles, nanofibers, and nanopolymers. These materials possess unique optical, mechanical, chemical, and thermal stability properties (Mal et al., 2022). In biomedical applications, diatom-derived nanostructures serve as contrast agents for magnetic resonance and ultrasound imaging, and as platforms for targeted delivery of therapeutic agents including medicines, catalysts, immunoglobulin, and genetic materials (D. Zhang et al., 2012).

XI. CONCLUSION AND FUTURE PERSPECTIVES

Heavy metal contamination has infiltrated diverse environmental compartments and continues to escalate due to anthropogenic activities. This growing concern has catalyzed extensive research aimed at elucidating mechanisms and developing effective strategies to mitigate its adverse impacts. Diatoms, recognized as bioindicators of heavy metal pollution in aquatic systems, remain underutilized despite their noteworthy potential. Challenges in isolation, cultivation, and large-scale propagation have limited their broader application. Diatoms represent one of the most promising biologically driven materials for heavy metal adsorption, with significant commercial and ecological value. However, substantial knowledge gaps persist in optimizing diatom-based wastewater treatment. Notably, no single diatom species has demonstrated universal tolerance to all heavy metals, highlighting the need for broader species screening and functional characterization.

Future research must prioritize the deployment of diatom-mediated remediation in full-scale bioreactors, such as open pond systems. These platforms must accommodate dynamic physicochemical variables, including temperature, seasonal fluctuations, pH, dissolved oxygen levels, photoperiods, and microbial consortia—that critically influence bioremediation efficacy. Although establishing and regulating these parameters poses technical challenges, it remains a feasible and worthwhile endeavor. While numerous studies have validated the phycoremediation potential of diatoms, the development of a scalable, economically viable, and environmentally sustainable technology is still in progress. Bridging these gaps will be essential to harness the full potential of diatoms in combating heavy metal pollution and advancing circular bioeconomy frameworks.

REFRENCES

1. Adey, W. H., Kangas, P. C., & Mulbry, W. (2011). Algal turf scrubbing: Cleaning surface waters with solar energy while producing a biofuel. Bioscience, 61(6), 434–441.
2. Armbrust, E. V. (2009). The life of diatoms in the world's oceans. Nature, 459(7244), 185–192.
3. Armbrust, E. V., Berges, J. A., Bowler, C., Green, B. R., Martinez, D., Putnam, N. H., Zhou, S., Allen, A. E., Apt, K. E., Bechner, M., Brzezinski, M. A., Chaal, B. K., Chiovitti, A., Davis, A. K., Demarest, M. S., Detter, J. C., Glavina, T., Goodstein, D., Hadi, M. Z., … Rokhsar, D. S. (2004). The Genome of the Diatom Thalassiosira Pseudonana: Ecology, Evolution, and Metabolism. Science, 306(5693), 79–86. https://doi.org/10.1126/science.1101156
4. Bach, L. T., Hernández-Hernández, N., Taucher, J., Spisla, C., Sforna, C., Riebesell, U., & Arístegui, J. (2019). Effects of elevated CO 2 on a natural diatom community in the subtropical NE Atlantic. Frontiers in Marine Science, 6, 75.
5. Bhaskar, M. V., Tiwari, A., & Rashed, J. N. (2016). Phycoremediation of eutrophic lakes using diatom algae. Lake Sciences and Climate Change, 103.
6. Briffa, J., Sinagra, E., & Blundell, R. (2020). Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon, 6(9).
7. Cavalier-Smith, T. (2018). Kingdom Chromista and its eight phyla: A new synthesis emphasising periplastid protein targeting, cytoskeletal and periplastid evolution, and ancient divergences. Protoplasma, 255(1), 297–357. https://doi.org/10.1007/s00709-017-1147-3
8. Cuellar-Bermudez, S. P., Aleman-Nava, G. S., Chandra, R., Garcia-Perez, J. S., Contreras-Angulo, J. R., Markou, G., Muylaert, K., Rittmann, B. E., & Parra-Saldivar, R. (2017). Nutrients utilization and contaminants removal. A review of two approaches of algae and cyanobacteria in wastewater. Algal Research, 24, 438–449.
9. Datta, A., Marella, T. K., Tiwari, A., & Wani, S. P. (2019). The Diatoms: From Eutrophic Indicators to Mitigators. In S. K. Gupta & F. Bux (Eds.), Application of Microalgae in Wastewater Treatment (pp. 19–40). Springer International

Publishing. https://doi.org/10.1007/978-3-030-13913-1_2

10. Deng, G., Zhang, T., Yang, L., & Wang, Q. (2013). Studies of biouptake and transformation of mercury by a typical unicellular diatom Phaeodactylum tricornutum. Chinese Science Bulletin, 58(2), 256–265. https://doi.org/10.1007/s11434-012-5514-3
11. Ding, T., Yang, M., Zhang, J., Yang, B., Lin, K., Li, J., & Gan, J. (2017). Toxicity, degradation and metabolic fate of ibuprofen on freshwater diatom Navicula sp. Journal of Hazardous Materials, 330, 127–134.
12. Fu, W., Nelson, D. R., Yi, Z., Xu, M., Khraiwesh, B., Jijakli, K., Chaiboonchoe, A., Alzahmi, A., Al-Khairy, D., & Brynjolfsson, S. (2017). Bioactive compounds from microalgae: Current development and prospects. Studies in Natural Products Chemistry, 54, 199–225.
13. Ganeshkumar, V., Subashchandrabose, S. R., Dharmarajan, R., Venkateswarlu, K., Naidu, R., & Megharaj, M. (2018). Use of mixed wastewaters from piggery and winery for nutrient removal and lipid production by Chlorella sp. MM3. Bioresource Technology, 256, 254–258.
14. Gautam, P. K., Gautam, R. K., Banerjee, S., Chattopadhyaya, M. C., & Pandey, J. D. (2016). Heavy metals in the environment: Fate, transport, toxicity and remediation technologies. Nova Sci Publishers, 60, 101–130.
15. Goh, S.-H., Yusoff, F. M., & Loh, S.-P. (2010). A comparison of the antioxidant properties and total phenolic content in a diatom, Chaetoceros sp. And a green microalga, Nannochloropsis sp. Journal of Agricultural Science, 2(3), 123.
16. Gouveia, L., Graça, S., Sousa, C., Ambrosano, L., Ribeiro, B., Botrel, E. P., Neto, P. C., Ferreira, A. F., & Silva, C. M. (2016). Microalgae biomass production using wastewater: Treatment and costs: Scale-up considerations. Algal Research, 16, 167–176.
17. Graham, J. M., Graham, L. E., Zulkifly, S. B., Pfleger, B. F., Hoover, S. W., & Yoshitani, J. (2012). Freshwater diatoms as a source of lipids for biofuels. Journal of Industrial Microbiology and Biotechnology, 39(3), 419–428.
18. He, Z. L., Yang, X. E., & Stoffella, P. J. (2005). Trace elements in agroecosystems and impacts on the environment. Journal of Trace Elements in Medicine and Biology, 19(2–3), 125–140.
19. Herawati, N., Suzuki, S., Hayashi, K., Rivai, I. F., & Koyama, H. (2000). Cadmium, copper, and zinc levels in rice and soil of Japan, Indonesia, and China by soil type. Bulletin of Environmental Contamination & Toxicology, 64(1).
20. Hernández-Ávila, J., Salinas-Rodríguez, E., Cerecedo-Sáenz, E., Reyes-Valderrama, M. I., Arenas-Flores, A., Román-Gutiérrez, A. D., & Rodríguez-Lugo, V. (2017). Diatoms and their capability for heavy metal removal by cationic exchange. Metals, 7(5), 169.
21. Huang, Z., Jones, J., Gu, J., Hallerman, E., Lane, T., Song, X., & Wan, R. (2013). Performance of a recirculating aquaculture system utilizing an algal turf scrubber for scaled-up captive rearing of freshwater mussels (Bivalvia: Unionidae). North American Journal of Aquaculture, 75(4), 543–547.
22. Jin, C., Yu, Z., Peng, S., Feng, K. E., Zhang, L., & Zhou, X. (2018). The characterization and comparison of exopolysaccharides from two benthic diatoms with different biofilm formation abilities. Anais Da Academia Brasileira de Ciências, 90(02), 1503–1519.
23. John, Y., David, V. E., & Mmereki, D. (2018). A Comparative Study on Removal of Hazardous Anions from Water by Adsorption: A Review. International Journal of Chemical Engineering, 2018, 1–21. https://doi.org/10.1155/2018/3975948
24. Koedooder, C., Guéneuguès, A., Van Geersdaële, R., Vergé, V., Bouget, F.-Y., Labreuche, Y., Obernosterer, I., & Blain, S. (2018). The role of the glyoxylate shunt in the acclimation to iron limitation in marine heterotrophic bacteria. Frontiers in Marine Science, 5, 435.
25. Köhler, L., Machill, S., Werner, A., Selzer, C., Kaskel, S., & Brunner, E. (2017). Are diatoms “green” aluminosilicate synthesis microreactors for future catalyst production? Molecules, 22(12), 2232.
26. Kumar, K. S., Dahms, H.-U., Won, E.-J., Lee, J.-S., & Shin, K.-H. (2015). Microalgae–a promising tool for heavy metal remediation. Ecotoxicology and Environmental Safety, 113, 329–352.

27. Lane, T. W., & Morel, F. M. M. (2000). A biological function for cadmium in marine diatoms. Proceedings of the National Academy of Sciences, 97(9), 4627–4631. https://doi.org/10.1073/pnas.090091397
28. Lee, J.-B., Hayashi, K., Hirata, M., Kuroda, E., SUZuki, E., Kubo, Y., & Hayashi, T. (2006). Antiviral sulfated polysaccharide from Navicula directa, a diatom collected from deep-sea water in Toyama Bay. Biological and Pharmaceutical Bulletin, 29(10), 2135–2139.
29. Lin, Z., Li, J., Luan, Y., & Dai, W. (2020). Application of algae for heavy metal adsorption: A 20-year meta-analysis. Ecotoxicology and Environmental Safety, 190, 110089.
30. Lobo, E. A., Heinrich, C. G., Schuch, M., Wetzel, C. E., & Ector, L. (2016). Diatoms as Bioindicators in Rivers. In O. Necchi Jr (Ed.), River Algae (pp. 245–271). Springer International Publishing. https://doi.org/10.1007/978-3-319-31984-1_11
31. Loix, C., Huybrechts, M., Vangronsveld, J., Gielen, M., Keunen, E., & Cuypers, A. (2017). Reciprocal interactions between cadmium-induced cell wall responses and oxidative stress in plants. Frontiers in Plant Science, 8, 1867.
32. Łukowski, A., & Dec, D. (2018). Influence of Zn, Cd, and Cu fractions on enzymatic activity of arable soils. Environmental Monitoring and Assessment, 190(5), 278. https://doi.org/10.1007/s10661-018-6651-1
33. Mal, N., Srivastava, K., Sharma, Y., Singh, M., Rao, K. M., Enamala, M. K., Chandrasekhar, K., & Chavali, M. (2022). Facets of diatom biology and their potential applications. Biomass Conversion and Biorefinery, 12(5), 1959–1975. https://doi.org/10.1007/s13399-020-01155-5
34. Mann, D. G., & Droop, S. J. M. (1996). 3. Biodiversity, biogeography and conservation of diatoms. Hydrobiologia, 336(1–3), 19–32. https://doi.org/10.1007/BF00010816
35. Marella, T. K., Datta, A., Patil, M. D., Dixit, S., & Tiwari, A. (2019). Biodiesel production through algal cultivation in urban wastewater using algal floway. Bioresource Technology, 280, 222–228.
36. Marella, T. K., Saxena, A., & Tiwari, A. (2020). Diatom mediated heavy metal remediation: A review. Bioresource Technology, 305, 123068.
37. Masindi, V., & Muedi, K. L. (2018). Environmental contamination by heavy metals. Heavy Metals, 10(4), 115–133.
38. Mehta, S. K., & Gaur, J. P. (2005). Use of Algae for Removing Heavy Metal Ions From Wastewater: Progress and Prospects. Critical Reviews in Biotechnology, 25(3), 113–152. https://doi.org/10.1080/07388550500248571
39. Morozov, A. A., & Galachyants, Y. P. (2019). Diatom genes originating from red and green algae: Implications for the secondary endosymbiosis models. Marine Genomics, 45, 72–78.
40. Mu, W., Chen, Y., Liu, Y., Pan, X., & Fan, Y. (2018). Toxicological effects of cadmium and lead on two freshwater diatoms. Environmental Toxicology and Pharmacology, 59, 152–162.
41. Nieri, P., Carpi, S., Esposito, R., Costantini, M., & Zupo, V. (2023). Bioactive molecules from marine diatoms and their value for the nutraceutical industry. Nutrients, 15(2), 464.
42. Nwoba, E. G., Parlevliet, D. A., Laird, D. W., Alameh, K., & Moheimani, N. R. (2019). Light management technologies for increasing algal photobioreactor efficiency. Algal Research, 39, 101433.
43. Ouyang, W., Wang, Y., Lin, C., He, M., Hao, F., Liu, H., & Zhu, W. (2018). Heavy metal loss from agricultural watershed to aquatic system: A scientometrics review. Science of the Total Environment, 637, 208–220.
44. Perales-Vela, H. V., Peña-Castro, J. M., & Canizares-Villanueva, R. O. (2006). Heavy metal detoxification in eukaryotic microalgae. Chemosphere, 64(1), 1–10.
45. Rebelo, F. M., & Caldas, E. D. (2016). Arsenic, lead, mercury and cadmium: Toxicity, levels in breast milk and the risks for breastfed infants. Environmental Research, 151, 671–688.
46. Rizwan, M., Ali, S., Rehman, M. Z. U., & Maqbool, A. (2019). A critical review on the effects of zinc at toxic levels of cadmium in plants. Environmental Science and Pollution Research, 26(7), 6279–6289. https://doi.org/10.1007/s11356-019-04174-6
47. Sawant, S. S., Khadamkar, H. P., Mathpati, C. S., Pandit, R., & Lali, A. M. (2018). Computational and experimental studies of high depth algal

raceway pond photo-bioreactor. Renewable Energy, 118, 152–159.

48. Shallari, S., Schwartz, C., Hasko, A., & Morel, J.-L. (1998). Heavy metals in soils and plants of serpentine and industrial sites of Albania. Science of the Total Environment, 209(2–3), 133–142.
49. Sims, P. A., Mann, D. G., & Medlin, L. K. (2006). Evolution of the diatoms: Insights from fossil, biological and molecular data. Phycologia, 45(4), 361–402. https://doi.org/10.2216/05-22.1
50. Sunday, E. R., Uyi, O. J., & Caleb, O. O. (2018). Phycoremediation: An eco-solution to environmental protection and sustainable remediation. J Chem Environ Biol Eng, 2(1), 5–10.
51. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy Metal Toxicity and the Environment. In A. Luch (Ed.), Molecular, Clinical and Environmental Toxicology (Vol. 101, pp. 133–164). Springer Basel. https://doi.org/10.1007/978-3-7643-8340-4_6
52. Tiwari, A., & Marella, T. K. (2019). Potential and Application of Diatoms for Industry-Specific Wastewater Treatment. In S. K. Gupta & F. Bux (Eds.), Application of Microalgae in Wastewater Treatment (pp. 321–339). Springer International Publishing. https://doi.org/10.1007/978-3-030-13913-1_15
53. Tripathi, S., & Poluri, K. M. (2021). Metallothionein-and Phytochelatin-Assisted Mechanism of Heavy Metal Detoxification in Microalgae. In M. Hasanuzzaman (Ed.), Approaches to the Remediation of Inorganic Pollutants (pp. 323–344). Springer Singapore. https://doi.org/10.1007/978-981-15-6221-1_16
54. Uthappa, U. T., Brahmkhatri, V., Sriram, G., Jung, H.-Y., Yu, J., Kurkuri, N., Aminabhavi, T. M., Altalhi, T., Neelgund, G. M., & Kurkuri, M. D. (2018). Nature engineered diatom biosilica as drug delivery systems. Journal of Controlled Release, 281, 70–83.
55. Utomo, H. D., Tan, K. X. D., Choong, Z. Y. D., Yu, J. J., Ong, J. J., & Lim, Z. B. (2016). Biosorption of heavy metal by algae biomass in surface water. Journal of Environmental Protection, 7(11), 1547.
56. Valko, M., Morris, H., & Cronin, M. T. D. (2005). Metals, toxicity and oxidative stress. Current Medicinal Chemistry, 12(10), 1161–1208.
57. Volland, S., Bayer, E., Baumgartner, V., Andosch, A., Lütz, C., Sima, E., & Lütz-Meindl, U. (2014). Rescue of heavy metal effects on cell physiology of the algal model system Micrasterias by divalent ions. Journal of Plant Physiology, 171(2), 154–163.
58. Wagner, H., Jakob, T., & Wilhelm, C. (2006). Balancing the energy flow from captured light to biomass under fluctuating light conditions. New Phytologist, 169(1).
59. Walker, C. H., Sibly, R. M., Hopkin, S. P., & Peakall, D. B. (2012). Principles of Ecotoxicology, Fourth Edition. CRC Press.
60. Wang, L. K., Chen, J. P., Hung, Y.-T., & Shammas, N. K. (2009). Heavy metals in the environment. CRC press.
61. Wang, X.-W., Huang, L., Ji, P.-Y., Chen, C.-P., Li, X.-S., Gao, Y.-H., & Liang, J.-R. (2019). Using a mixture of wastewater and seawater as the growth medium for wastewater treatment and lipid production by the marine diatom Phaeodactylum tricornutum. Bioresource Technology, 289, 121681.
62. Winter, J. G., & Duthie, H. C. (2000). Stream epilithic, epipelic and epiphytic diatoms: Habitat fidelity and use in biomonitoring. Aquatic Ecology, 34(4), 345–353. https://doi.org/10.1023/A:1011461727835
63. Yan, Z., Kangas, P. C., Yuan, X., Chen, Y., Zhang, Y., Li, J., Su, Y., Gao, X., & Chen, N. (2018). Flow conditions influence nutrient removal at an artificial lake and a drinking water reservoir with an algal floway. Algal Research, 35, 245–252.
64. Zhang, D., Wang, Y., Cai, J., Pan, J., Jiang, X., & Jiang, Y. (2012). Bio-manufacturing technology based on diatom micro- and nanostructure. Chinese Science Bulletin, 57(30), 3836–3849. https://doi.org/10.1007/s11434-012-5410-x
65. Zhang, J., Ding, T., Zhang, Z., Xu, L., & Zhang, C. (2015). Enhanced adsorption of trivalent arsenic from water by functionalized diatom silica shells. PloS One, 10(4), e0123395.