

Harnessing Diatoms to Mitigate Microplastic Pollution: A Review

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Abstract- Microplastic (MP) pollution has become a critical environmental issue, with particles originating from consumer products and plastic degradation now pervasive in aquatic, terrestrial, and atmospheric systems. MPs pose ecological risks by disrupting feeding, growth, and reproduction in aquatic organisms and potentially entering human food chains. Traditional mitigation strategies remain insufficient, prompting exploration of biological alternatives. Diatoms, photosynthetic microalgae with silica frustules, show strong potential for MP remediation. Through biofilm formation, extracellular polymeric substance (EPS) secretion, and adhesion, diatoms facilitate MP aggregation, sedimentation, and partial degradation. Their interactions with bacteria further enhance plastic breakdown, while large-scale cultivation enables integration into wastewater treatment and hybrid remediation systems. Despite limitations such as incomplete degradation and environmental dependence, diatoms represent an eco-friendly, scalable, and sustainable strategy. Advances in engineered consortia, genetic modification, and field validation may establish diatoms as a viable biotechnological tool for mitigating microplastic pollution.

Keywords: Microplastic Mitigation, Diatoms, Pollution, Microalgae.

I. INTRODUCTION

Since their large-scale introduction in the 1950s, plastics have become an integral part of modern life, with global production increasing from 0.5 million tons in 1960 to 348 million tons by 2017 (Barnes et al., 2009). While highly versatile, plastics degrade extremely slowly, leading to accumulation in terrestrial and aquatic environments (Barnes et al., 2009). Over time, attention has shifted from macroplastics to tiny plastic particles smaller than 5 millimeters called microplastics (MPs), although some researchers suggest thresholds as small as 1 millimeter (Gigault et al., 2018; Hartmann et al., 2019).

MPs have become a pressing environmental concern due to their ubiquity, persistence, and potential risks to ecosystems and human health. They enter the environment through multiple pathways, including the fragmentation of larger plastic debris, shedding from synthetic textiles, and the release of microbeads from personal care products (Galgani et al., 2021). Once released, MPs disperse widely, contaminating oceans, rivers, lakes, sediments, soils, and even remote regions such as polar areas, where they have been detected in sea ice cores (Peeken et al., 2018; Watteau et al., 2018). Although oceans

directly receive only a small fraction of primary MPs, rivers serve as critical conduits, transporting the majority of land-based plastic debris to marine systems (Boucher and Friot, 2017). Recent studies have also identified MPs in farmlands, wastewater systems, sewage sludge, and atmospheric deposition (Hu et al., 2019; Chen et al., 2020).

Microplastics affect organisms across multiple trophic levels. MPs can be ingested accidentally or deliberately by small invertebrates and fish, leading to reduced feeding efficiency, lower energy uptake, and subsequent declines in growth, reproduction, and survival (Karami et al., 2016; Windsor et al., 2019).

In microalgae, exposure to MPs can alter chlorophyll content, photosynthetic activity, and reactive oxygen species production, although these effects are typically observed at unrealistically high concentrations (Prata et al., 2019). Despite these insights, most ecotoxicological studies have focused on marine organisms, while freshwater and terrestrial species remain less studied (Anderson et al., 2016; Chae and An, 2018).

Diatoms being a diverse group of unicellular algae with silica-based frustules, are essential to aquatic

ecosystems. They form the base of aquatic food webs, supporting zooplankton, small fish, and other filter-feeding organisms (Trequer et al., 1995; Field et al., 1998; Naz et al., 2025).

Diatoms also play a pivotal role in nutrient cycling and serve as bioindicators due to their sensitivity to changes in water quality (Taylor et al., 2007; Stevenson et al., 2008). Despite their ecological importance, interactions between diatoms and MPs remain poorly understood. Physical contact, adsorption, and ingestion of MPs by diatoms could potentially affect their physiology, growth, and ecological function, thereby influencing broader food web dynamics (Bryant et al., 2016; Long et al., 2015; Yokota et al., 2017).

Beyond their ecological roles, diatoms can also mitigate microplastic pollution. Their frustules and extracellular polymeric substances (EPS) can adsorb MPs, facilitating aggregation and sedimentation, which removes MPs from the water column and reduces their bioavailability (Long et al., 2015; Yokota et al., 2017). Such interactions highlight the potential of diatoms as natural bio-filters in aquatic systems, partially controlling the spread and ecological impact of MPs.

The widespread presence of MPs underscores the urgency of understanding their ecological consequences. Monitoring remains challenging due to the small size, heterogeneity, and multiple sources of microplastics, necessitating advanced analytical techniques such as microscopy, spectroscopy, and chemical characterization (Galgani et al., 2021). With nearly 98% of MPs originating from land-based activities, effective waste management and mitigation strategies are critical to reducing environmental release (Boucher and Friot, 2017).

Microplastics are a pervasive and complex environmental challenge and their interactions with primary producers like diatoms, which underpin aquatic food webs, are crucial for understanding ecosystem-level impacts. Diatoms not only form a key component of aquatic food webs but may also mitigate MPs through adsorption and sedimentation, reducing environmental exposure.

Comprehensive research on the sources, ecological effects, and management of MPs is essential to safeguard aquatic ecosystems and the organisms that depend on them (Eriksen et al., 2014).

Microplastics: Sources, Pathways, and Impact

Sources

The microplastics are found to be originated by two main sources by the breakdown of meso- and macroplastics debris or directly by the runoffs. Microplastics, especially the manufactured microplastics and nanoparticles of plastics which are used in consumer products gets introduced into the oceans directly via runoff (Maynard, 2006).

It generally include micron-sized plastic particles mainly used in synthetic 'sandblasting' media (beads of acrylic plastics and polyester), as exfoliants in cosmetic formulations (Gregory, 1996; Fendall and Sewell, 2009), those generated in ship-breaking industry and industrial abrasives. The different sources of microplastic is shown in figure 1, majority of microplastics are generated by the in situ weathering of mesoplastics and larger fragments of plastic litter (Gregory and Andrady, 2003).

Primary Microplastics can be categorised as Microbeads, Microfibers and Nurdles or Pellets. Microbeads are tiny plastic particles used in personal care and cosmetic products such as exfoliating scrubs and toothpaste. They are intentionally manufactured and added to these products. Microfibers includes the microscopic plastic fibers shed from synthetic textiles during washing and other activities, fabrics like polyester, nylon, and acrylic are common sources while the nurdles (or pellets) are pre-production plastic pellets used in the manufacturing of plastic products. Accidental spills during transport or manufacturing contribute to the presence of nurdles in the environment.

The secondary microplastics are generally formed by the fragmentation of larger plastic items, such as bottles and bags, break down over time due to weathering and UV radiation, forming smaller microplastics particles (Bryant et al., 2016).

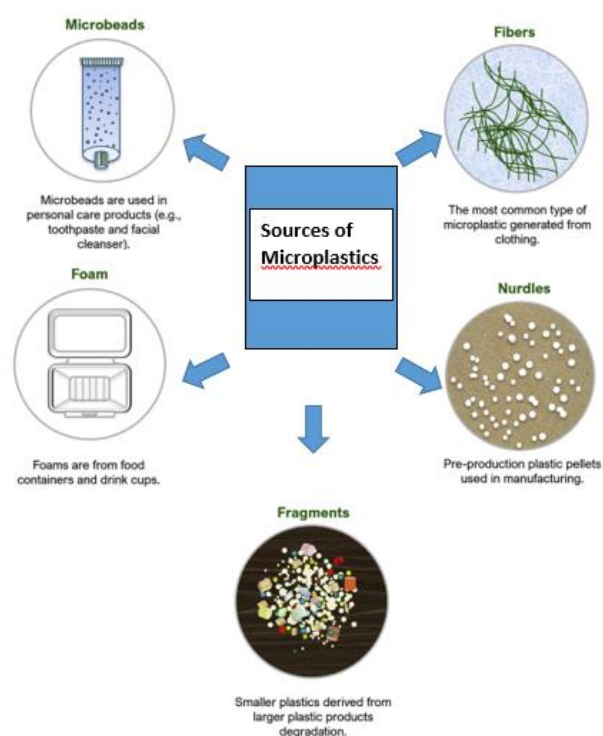


Figure 1: Showing different sources of microplastics

Pathways of Microplastics

Microplastics are distributed widely across various environmental compartments, including oceans, rivers, soil, air, and even some freshwater and terrestrial ecosystems. The distribution of microplastics is influenced by a combination of natural processes and human activities. Microplastics have now become nearly ubiquitous and can be found in most of the places. Plastic waste enters the natural environment after its degradation into smaller particles due to photo oxidation, weathering, and mechanical and biological degradation, resulting in microplastics (Cole M et al., 2011).

In aquatic systems, they enter rivers, lakes, and oceans through urban runoff, industrial discharges, wastewater, and atmospheric deposition. Activities such as shipping, fishing, and improper waste disposal further release plastics directly into water bodies. Rivers serve as key transport routes, carrying microplastics from inland areas to the sea (Cai et al., 2021). Once in marine environments, ocean currents

and tides move and redistribute these particles, depositing them everywhere from coastlines and surface waters to deep-sea sediments and even Polar Regions. Studies have already documented microplastics in plankton, fish, and seabirds, showing how deeply they have penetrated aquatic food webs. On beaches and coastlines, plastic litter experiences rapid weathering due to high temperatures and direct sunlight. By contrast, in deeper marine zones, fragmentation occurs more slowly, but the eventual result is the same: continuous formation of microplastics.

In the atmosphere, microplastics can be carried by wind and deposited back into land or water through atmospheric fallout. Airborne transport allows them to reach even remote regions, highlighting their global mobility (Belioka & Achilias., 2024).

In soils, microplastics accumulate through multiple routes: irrigation with contaminated water, the use of plastic-containing fertilizers, atmospheric deposition, or the breakdown of larger debris. Unlike in water, plastics degrade very slowly in soils due to limited sunlight and reduced mechanical wear (Allen et al., 2020). Over time, soils become long-term sinks of microplastics, which can alter important properties such as water retention, bulk density, and permeability. This raises concerns about agricultural productivity and food safety.

Ultimately, these particles do not just stay in the environment, they move into living organisms. Fish, mollusks, plankton, insects, and birds ingest them, introducing plastics into both aquatic and terrestrial food chains. Humans are also exposed through seafood, bottled water, and even tap water, making microplastic pollution a widespread ecological and public health challenge (Sharma and Chatterjee et al., 2017).

Impacts of Microplastics

Microplastics persist in the environment for decades and their impacts are felt across ecosystems, human health, and the economy. In aquatic environments, these tiny particles are easily ingested by fish, mollusks, plankton, and other organisms. This can cause physical harm, disrupt feeding and

reproduction, and introduce plastics into the food web, with the potential to accumulate through higher trophic levels (Ghosh et al., 2023). Similarly, in terrestrial ecosystems, insects, birds, and soil organisms may ingest or interact with microplastics, which can alter habitat quality and overall ecosystem balance. The effects on human health remain an area of active research.

Microplastics have been detected in seafood, bottled water, and even tap water, showing clear pathways for human exposure. While the long-term health risks are still uncertain, concerns include possible inflammation, toxic chemical leaching, and bioaccumulation within human tissues (Smith et al., 2018). Beyond ecological and health concerns, microplastic pollution also creates economic burdens.

The sources and ecological consequences of microplastics is are summarized in figure 2.

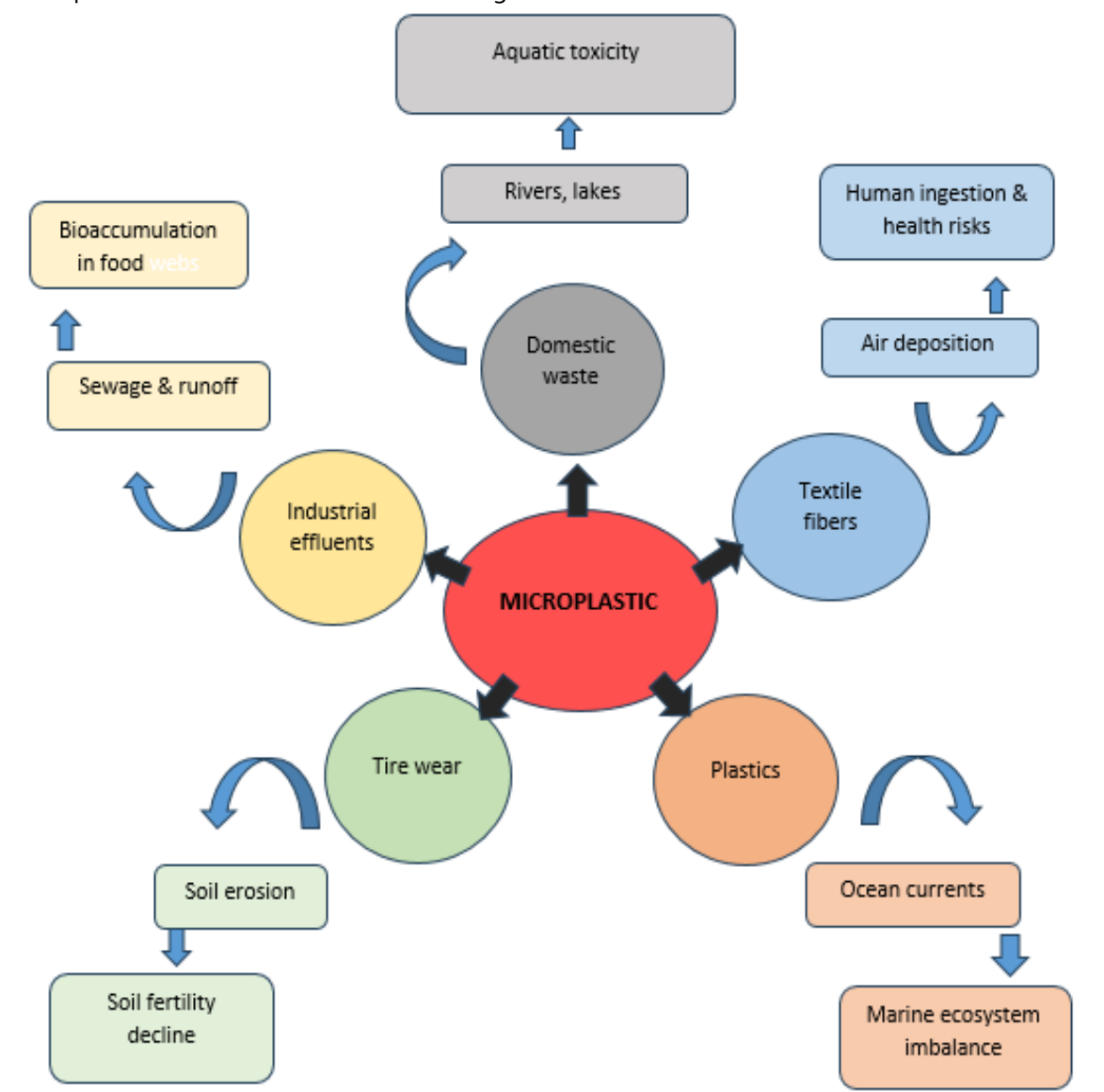


Figure 2: Showing source and impact of Microplastics

Industries such as fisheries, agriculture, and tourism face losses due to declining ecosystem health and pollution of natural resources. Additionally, governments and communities must bear the costs of cleanup and mitigation, diverting resources that could be used for other development needs.

Given these persistent challenges, biological mitigation strategies are gaining attention. Among them, diatoms, microscopic algae with silica-based cell walls show promising potential (Roychoudhury et al., 2022), can interact with microplastics in several ways: they attach to and colonize plastic surfaces, promoting biofilm formation that accelerates plastic degradation; they contribute to bioremediation by trapping and sinking microplastics through their natural sedimentation; and their silica frustules may act as natural filters, reducing particle mobility in aquatic systems. Furthermore, diatom-driven processes can enhance microbial activity, facilitating the breakdown of plastic polymers.

II. MECHANISMS OF INTERACTION BETWEEN DIATOMS AND MICROPLASTICS

Biofilm Formation and Adhesion

Diatoms easily establish intricate biofilms on synthetic substrates, such as plastic surfaces. Often called the "plastisphere," these biofilms are made up of bacteria, diatoms, and extracellular polymeric substances (EPS).

By decreasing MPs' buoyancy and promoting sedimentation, the sticky EPS that diatoms exude improves MPs' adhesion to organic materials and living things. For instance, it has been documented that *Navicula* and *Cocconeis* species may colonize polyethylene and polystyrene in a matter of weeks, changing the MPs' surface hydrophobicity (Sapozhnikov et al., 2021).

Aggregation and Flocculation

The natural flocculant EPS that diatoms make binds MPs to organic debris and to each other. By forming bigger, denser particles, this aggregation effectively removes MPs from the water column by sinking them to the sediment. Comparable to the "biological

carbon pump," this method implies that diatoms might obliquely aid in the sequestration of MPs in benthic zones.

Biotechnological Applications

Diatoms also hold great potential for tackling microplastic pollution through biotechnological innovations. In engineered systems such as photobioreactors, diatoms form biofilms that enhance microplastic capture while purifying wastewater (Nyakundi et al., 2023).

Scientists are also exploring genetic engineering to boost EPS production or introduce enzymes like PETase that can degrade plastic polymers (Martín-González et al. 2024). Moreover, diatom shells can be functionalized with magnetic or photocatalytic materials to create advanced filters that both capture and break down plastics. These energy-efficient and sustainable systems make diatoms a powerful biological tool for mitigating microplastic pollution and restoring the health of aquatic ecosystems.

Synergistic Role with Bacteria

Although diatoms by themselves would not be able to break down synthetic polymers enzymatically, bacteria that can partially depolymerize plastic can be found in their biofilms (Chen et al., 2020). By producing a microenvironment that is abundant in oxygen, reactive oxygen species (ROS), and enzymes, the diatom-bacteria consortium increases the potential for MP breakdown. This demonstrates how diatoms function as ecosystem engineers that promote the breakdown of plastic by microbes.

Oxidative Weathering

Diatom photosynthesis can accelerate the oxidation of plastic surfaces by releasing oxygen and, on occasion, reactive oxygen species (ROS). According to Shah et al. (2008), oxidized polymers are more vulnerable to microbial attack because of their enhanced hydrophilicity. Despite its slightness, this result suggests a possible synergistic mechanism for plastic weathering aided by diatoms.

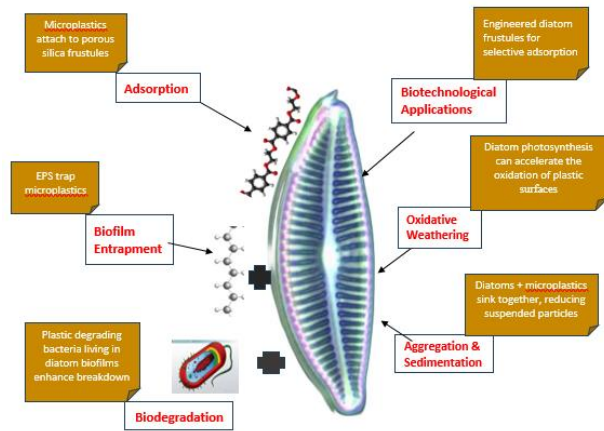


Figure 3: Showing mitigation mechanisms of microplastics through diatoms

III. ADVANTAGES OF USING DIATOMS

Eco-Friendly and Sustainable

Diatoms rely only on light, CO₂, and nutrients, making them self-sustaining and environmentally benign. Being unicellular photosynthetic organisms they form biofilms on plastic surfaces, aiding in the biodegradation of microplastics without producing toxic byproducts. Their natural capacity to colonize and metabolize plastics allows them to use plastic-derived monomers as a carbon source by releasing appropriate enzymes.

This process reduces the persistence and toxicity of microplastics without requiring chemical additives or harsh physical treatments. Diatoms are abundant, self-propagating primary producers in aquatic ecosystems (Srivastava et al., 2025), ensuring continuous availability for microplastic mitigation. They thrive in a wide range of water bodies and naturally form part of the ecological succession on plastic surfaces, leading to biodegradation and biofouling that ultimately increases the sinking and breakdown of plastics.

Integration of diatoms or consortia containing diatoms into bioremediation systems supports long-term, low-cost solutions that minimize secondary pollution and energy consumption. The use of diatoms for microplastic mitigation leverages their eco-friendly, sustainable nature, fostering safer and

more resilient aquatic ecosystems while minimizing additional ecological impact

Dual Benefits

In addition to mitigating MPs, diatoms play a crucial role in enhancing water quality by actively removing excess nutrients like nitrogen and phosphorus, which are primary contributors to eutrophication and harmful algal blooms; their ability to assimilate these nutrients helps maintain a balanced aquatic ecosystem, reduce the occurrence of water quality issues, and promote healthier habitats for aquatic life.

High Surface Affinity

Diatoms attach efficiently to microplastics (MPs) through a combination of structural and biochemical mechanisms, primarily involving their silica frustules and extracellular polymeric substances (EPS). Silica frustules, the rigid and intricately patterned cell walls of diatoms, provide a high-surface-area scaffold that can physically anchor the cells onto plastic surfaces.

The micro- and nano-scale ridges, pores, and spines on frustules increase contact points with the hydrophobic surfaces of plastics, facilitating stable attachment even in flowing water. Complementing this, diatoms secrete EPS, a sticky matrix of polysaccharides, proteins, and lipids, which acts as a biological glue. EPS not only binds diatoms to plastic surfaces but also promotes the aggregation of multiple cells, forming dense biofilms. These biofilms enhance microplastic sedimentation by increasing particle weight and enabling colonization by other microorganisms, accelerating microplastic degradation.

Diatom species like *Navicula* and *Nitzschia* are found to produce copious EPS that strongly adhere to polyethylene and polypropylene fragments, while *Cylindrotheca* frustules exhibit micro-spines that interlock with plastic surfaces, stabilizing early biofilm formation (Khan et al., 2020). Together, the rigid silica frustules and adhesive EPS allow diatoms to colonize a variety of microplastic types under diverse environmental conditions, making them key agents in biological microplastic mitigation strategies.

Scalability

Diatoms offer a practical and cost-effective approach for microplastic mitigation because they can be cultivated on a large scale under controlled conditions. They thrive in photobioreactors, which are engineered systems that provide optimal light, temperature, and nutrient conditions to maximize diatom growth and biomass production. These systems allow for continuous cultivation and can be tailored to produce species that are particularly effective at adhering to and forming biofilms on microplastics.

Beyond laboratory cultivation, diatoms can be integrated into wastewater treatment plants, where they naturally colonize plastic particles present in sewage or runoff. In these systems, diatoms form biofilms on microplastics, promoting aggregation, sedimentation, and eventual removal from water. Their growth in wastewater is supported by the abundant nutrients typically present, making the process energy-efficient and cost-effective compared to chemical or mechanical treatments. By leveraging large-scale cultivation and wastewater integration, diatom-based strategies offer a scalable, eco-friendly, and economically feasible solution for reducing microplastic pollution in aquatic environments.

IV. LIMITATIONS AND CHALLENGES

Incomplete Degradation

While diatoms are effective at trapping and sedimenting microplastics (MPs) through biofilm formation, their ability to fully break down plastic polymers is limited. The silica frustules and extracellular polymeric substances (EPS) facilitate adhesion and aggregation, allowing microplastics to settle in sediments and reducing their mobility in aquatic systems. However, diatoms rarely mineralize the plastics completely, meaning the polymers persist in the environment. Over time, this can lead to long-term accumulation of microplastics in sediments, where they may still pose ecological risks or re-enter food webs under certain conditions. Therefore, while diatom-mediated mitigation offers clear ecological benefits, it should be viewed as a complementary strategy alongside other physical,

chemical, or microbial degradation approaches for more comprehensive microplastic management. (Windsor et al., 2019).

Environmental Dependence

The effectiveness of diatoms in mitigating microplastics is strongly influenced by environmental conditions. Factors such as nutrient availability, temperature, salinity, and light exposure play critical roles in determining diatom growth, colonization, and biofilm formation on plastic surfaces. Warm temperatures and abundant nutrients, particularly nitrogen and phosphorus, accelerate metabolic activity and biofilm development (Sharma et al., 2023). Light availability is essential for photosynthetic growth, making floating plastics in sunlit waters more favorable for colonization. Salinity and water chemistry, including pH and dissolved oxygen, also shape species composition and adhesion efficiency. These dependencies mean that diatom-mediated mitigation is most effective under optimal environmental conditions, and strategies must consider site-specific factors to maximize biofilm formation and microplastic removal.

Biofilm Complexity

While diatom biofilms are central to microplastic mitigation, the complexity of these plastisphere communities introduces potential ecological concerns. Plastics in aquatic environments often host mixed-species biofilms, including bacteria, fungi, and other microorganisms alongside diatoms. Some of these microbes may be pathogenic or invasive, posing risks to aquatic organisms and potentially altering ecosystem dynamics. Additionally, interactions within these biofilms can influence nutrient cycling, chemical transformations, or microplastic aggregation in ways that are not fully understood. Therefore, while diatom-mediated biofilms aid in sedimentation and microplastic control, their formation must be monitored carefully to balance mitigation benefits with possible secondary ecological impacts. (Kettner et al., 2019).

Knowledge Gaps

Despite growing interest in using diatoms to mitigate microplastic pollution, significant knowledge gaps remain. The molecular and ecological mechanisms that govern diatom-plastic interactions such as adhesion, biofilm formation, and facilitation of microbial degradation are not yet fully elucidated. It is also unclear how factors like plastic type, surface chemistry, and environmental variability influence colonization efficiency across different ecosystems. Moreover, most studies have been conducted in controlled laboratory settings, and large-scale field trials are limited. This restricts our understanding of how diatom-mediated mitigation performs under real-world conditions, including its long-term effectiveness, ecological impacts, and scalability. Addressing these gaps is crucial to develop reliable and sustainable strategies for managing microplastic pollution in diverse aquatic environments.

V. FUTURE PROSPECTS

Engineered Consortia

To enhance the efficiency of diatom-mediated microplastic (MP) mitigation, researchers are exploring engineered consortia combining diatoms with plastic-degrading bacteria. Diatoms form biofilms on MP surfaces, creating a stable habitat, while associated bacteria can enzymatically break down plastic polymers. By selecting and co-culturing species with complementary abilities—strong adhesion, rapid biofilm formation, and high biodegradation potential. These consortia can accelerate MP removal and reduce persistence in aquatic environments. Such engineered systems can be applied in photobioreactors or integrated into wastewater treatment plants, providing a scalable and sustainable approach. This strategy leverages the synergistic interactions between diatoms and microbes, offering a promising avenue to overcome the limitations of diatoms alone in microplastic mitigation.

Genetic Engineering

Genetic engineering offers a promising strategy to boost the natural microplastic mitigation capabilities of diatoms. By modifying diatoms to overproduce

extracellular polymeric substances (EPS), their ability to adhere to and aggregate microplastic particles can be significantly enhanced, promoting faster biofilm formation and sedimentation. Similarly, engineering diatoms to produce higher levels of reactive oxygen species (ROS) could facilitate the oxidative breakdown of plastic polymers, accelerating degradation in aquatic environments. Such modifications can create highly efficient diatom strains capable of both trapping and partially degrading microplastics. When combined with large-scale cultivation in photobioreactors or integration into wastewater treatment systems, genetically enhanced diatoms could provide a scalable, eco-friendly, and more effective approach to tackling persistent microplastic pollution.

Hybrid Treatment Systems

Integrating diatom-based bioreactors with conventional wastewater treatment plants offers a hybrid approach that targets both microplastics (MPs) and nutrient pollutants simultaneously (Zhang et al., 2025). In such systems, diatoms form biofilms on MPs, enhancing aggregation and sedimentation, while naturally removing nutrients like nitrogen and phosphorus through uptake and growth. The hybrid setup leverages the complementary strengths of biological and mechanical treatment processes: conventional treatment removes bulk contaminants and solids, while diatom bioreactors improve the removal of microplastics and residual nutrients. This integration is cost-effective, scalable, and sustainable, providing an eco-friendly solution for reducing microplastic pollution and improving water quality in urban and industrial wastewater streams.

Sediment Management for microplastic mitigation

While diatoms and biofilm-mediated sedimentation effectively remove microplastics (MPs) from the water column, these particles often accumulate in sediments, posing a risk of secondary pollution if disturbed. Effective sediment management strategies are therefore essential to prevent reintroduction of MPs into aquatic ecosystems (Nikpay et al., 2024). Approaches may include controlled dredging, containment or stabilization of MP-rich sediments, and safe disposal or recycling

techniques. Coupling sediment management with biological treatments, such as diatom-mediated aggregation, can further reduce mobility and ecological risks. By addressing the fate of microplastics in sediments, these strategies ensure that mitigation efforts are comprehensive, preventing downstream contamination and maintaining the long-term health of aquatic environments.

Field Validation

To ensure that diatom-mediated strategies for microplastic (MP) mitigation are both effective and safe, it is essential to conduct real-world pilot studies. Field validation allows researchers to test how well diatoms form biofilms, aggregate microplastics, and facilitate sedimentation under natural environmental conditions, which can vary widely in temperature, nutrient availability, salinity, and light (Parikh et al., 2025). These studies also help assess ecological safety, monitoring potential impacts of biofilm communities on native organisms and ecosystems. Additionally, pilot trials provide critical data on cost-effectiveness and scalability, informing whether laboratory or wastewater-based strategies can be reliably implemented at larger scales. Field validation thus bridges the gap between experimental research and practical application, ensuring sustainable and ecologically responsible microplastic mitigation.

CONCLUSION

Diatoms, offer a promising biological approach to mitigate microplastic pollution through biofilm formation, attachment, and sedimentation. Their colonization on plastic surfaces is influenced by environmental, substrate, temporal, and biotic factors. Warm temperatures enhance metabolic activity, promoting faster attachment and thicker biofilms, with colonization typically peaking in spring and summer. High nutrient availability, particularly nitrogen and phosphorus, accelerates diatom growth and diversity, especially in productive aquatic habitats. Light exposure is crucial, as floating plastics in sunlit surface waters support optimal photosynthesis, whereas shaded or submerged plastics see slower colonization (Singh et al., 2025).

Water chemistry, including salinity, pH, and dissolved oxygen, also shapes diatom community structure. Figure 3 depicts the proposed mechanism of microplastic entrapment by benthic diatoms. Substrate characteristics such as plastic type, surface texture, hydrophobicity, and age determine the ease and stability of attachment, with floating plastics like polyethylene being most favorable. Temporal and spatial dynamics play a role, as longer submersion periods allow for mature, diverse biofilms, and early colonizers like *Cylindrotheca*, *Navicula*, and *Nitzschia* dominate initial succession (Sekar et al., 2004). By forming biofilms, diatoms can trap microplastics, facilitate microbial degradation, and enhance sedimentation, reducing their mobility in aquatic systems. Understanding these factors is essential to harness diatoms as a sustainable and eco-friendly tool for microplastic mitigation.

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