



Diatoms as Microbial Architects of the Silica Cycle: Ecological Significance, Biogenic Bioactives, and Emerging Biotechnological Applications

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Abstract

Diatoms are a diverse group of photosynthetic microorganisms that play a crucial role in global biogeochemical cycles, particularly the silica cycle. These microscopic algae are characterized by their intricate cell walls made of biogenic silica, which influences nutrient cycling, sediment formation, and the productivity of aquatic ecosystems. As primary producers, diatoms contribute significantly to oxygen production and carbon sequestration, making them essential for maintaining ecological balance in marine and freshwater environments. Their rapid reproduction and high efficiency in photosynthesis support diverse food webs and sustain marine biodiversity. The silica cycle, largely driven by diatoms, regulates the availability of dissolved silica in aquatic systems. By extracting silica from their surroundings, diatoms build their elaborate frustules, which eventually settle to the ocean floor upon their death, forming diatomaceous sediments. These sediments play a role in long-term carbon storage and influence oceanic chemical composition. Additionally, diatoms have gained interest in biotechnology and nanotechnology due

to their unique silica structures, which have potential applications in drug delivery, biosensors, and renewable energy technologies. Despite their ecological and industrial significance, diatom populations are vulnerable to environmental changes, including shifts in ocean temperature, nutrient availability, and acidification. Understanding their role in the silica cycle and their responses to changing conditions is crucial for predicting the impacts of climate change on marine productivity. This review explores the biological processes that enable diatoms to shape the silica cycle, their ecological importance, and their potential applications in modern science and technology. By examining their contributions to ecosystem stability and industrial innovation, this article highlights why diatoms remain one of nature's most important silica architects.

Keywords: Diatoms, Silica cycle, Biogenic silica, Carbon sequestration, Marine ecosystems.

1. Introduction

Diatoms serve as effective indicators for assessing environmental conditions. Diatom species are a concerning factor in the aquatic ecosystem for seasonal dynamics due to their diverse lifestyles, habitat variations, and regeneration mechanisms. Diatoms are classified as aquatic producer groups that rapidly respond to alterations in environmental factors (Tokatli et al., 2022). Planktonic and benthic diatoms contribute to seasonal fluctuations in species richness and community composition, with benthic diatom assemblages being more influenced by environmental conditions. Benthic diatoms, due to their robust association with ecological parameters, might be proposed as biotic indicators for

Significance | Diatoms drive microbial silica cycling and produce bioactive structures, advancing ecological sustainability, climate regulation, and biotechnological applications.

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monitoring and assessing the ecological condition of rivers (Ali et al., 2023; Hu et al., 2022). Microscopic assessment of biovolume enables great taxonomic precision, including species-level accuracy, and biovolume calculation is essential for evaluating the relative abundance (as biomass or carbon) of benthic diatoms, which vary in size and form. Estimating biomass using biovolume calculation is crucial for the majority of microbial plankton ecology research (Yang et al., 2022; Hasan et al., 2023).

Diatoms are a diverse and ecologically significant group of microalgae that play a fundamental role in aquatic ecosystems. As key primary producers, they contribute significantly to global oxygen production and carbon fixation, accounting for nearly 40% of marine primary productivity. Their distinguishing feature is their intricate cell walls, or frustules, which are composed of biogenic silica (SiO_2). These siliceous structures not only provide diatoms with structural integrity but also contribute to the cycling of silica in marine and freshwater environments. The silica cycle, primarily driven by diatom activity, is a crucial component of global biogeochemical processes, influencing nutrient availability, sediment deposition, and long-term carbon storage (Amin et al., 2012). The silica cycle begins with the weathering of silicate minerals on land, releasing dissolved silicic acid into rivers and coastal waters. Once in aquatic environments, diatoms absorb silicic acid and polymerize it into solid silica to construct their frustules. Upon the death of diatoms, their silica-rich frustules either dissolve back into the water column, making silica available for future biological uptake, or sink to the ocean floor, contributing to sediment formation. This process, known as the biological pump, plays a critical role in carbon sequestration by facilitating the transfer of organic matter from surface waters to deep-sea environments. Over geological time scales, diatomaceous sediments have led to the formation of extensive silica deposits, including diatomite and opal-rich marine sediments (Bailleul et al., 2015).

Diatoms are highly adaptable and thrive in diverse aquatic habitats, from oceanic waters to freshwater lakes and even ice-covered polar regions. Their success is attributed to their efficient nutrient uptake, rapid reproduction, and ability to form massive blooms in nutrient-rich conditions. Upwelling zones, where deep, nutrient-rich waters rise to the surface, are particularly favorable for diatom growth, making them dominant phytoplankton in regions such as the North Pacific and the Southern Ocean. These blooms serve as the foundation of marine food webs, providing a rich source of organic matter for zooplankton, fish, and higher trophic levels. Despite their ecological significance, diatoms are highly sensitive to environmental changes. Rising ocean temperatures, acidification, and shifts in nutrient availability can alter diatom population dynamics, potentially disrupting the silica cycle (Bowler et al., 2010). Additionally, anthropogenic activities such as agricultural runoff

and industrial pollution contribute to eutrophication, leading to harmful algal blooms that may outcompete diatoms and reduce silica availability. Understanding these challenges is essential for predicting future changes in marine productivity and ecosystem stability.

Beyond their ecological importance, diatoms have attracted scientific interest due to their intricate silica structures, which have potential applications in nanotechnology, biotechnology, and materials science. Their frustules exhibit nanoscale precision, making them valuable for drug delivery, biosensors, and optical devices. Additionally, research into diatom-inspired materials has led to advances in sustainable manufacturing and renewable energy technologies. By studying diatoms, scientists can gain insights into both ecological processes and innovative applications in material sciences. This review explores the multifaceted role of diatoms in the silica cycle. The first section examines their biological characteristics and the mechanisms behind silica biomineralization. The second section discusses their ecological impact, emphasizing their role in nutrient cycling and marine productivity (Brown et al., 2011). The third section delves into their contributions to carbon sequestration and climate regulation. The fourth section addresses environmental challenges affecting diatom populations, while the final section highlights their potential applications in nanotechnology and industrial innovations. By understanding diatoms as nature's silica architects, we can appreciate their contributions to both environmental sustainability and scientific advancement.

2. Biological Characteristics and Silica Biomineralization

Diatoms are unique among phytoplankton due to their siliceous cell walls, which are composed of hydrated silicon dioxide, commonly referred to as biogenic silica. These intricate and highly structured frustules are responsible for the remarkable diversity of diatom species, with estimates ranging from 100,000 to 200,000 different species (Brunner et al., 2009). The formation of these silica-based cell walls, a process known as biomineralization, is essential for diatom survival, influencing their ecological roles, competitive advantages, and contribution to global biogeochemical cycles.

2.1 Morphological and Structural Features of Diatoms

Diatoms exhibit a broad range of morphological adaptations, which can be broadly categorized into two main groups: centric diatoms and pennate diatoms. Centric diatoms, which are primarily found in marine environments, possess a radial symmetry that enables them to thrive in open ocean waters. Pennate diatoms, in contrast, are characterized by bilateral symmetry and are more common in freshwater and benthic environments, where they attach to surfaces such as sediments, rocks, and aquatic vegetation. The frustule of a diatom consists of two overlapping silica plates, known as the epitheca and hypotheca, which fit together like a petri dish. This

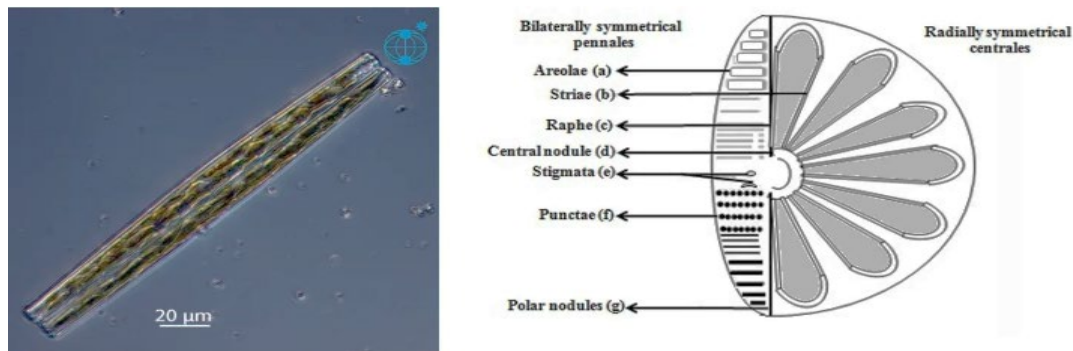


Figure 1. Structure of Diatoms (courtesy of image from Malviya et al.,2016)

rigid structure provides protection from predation while allowing diatoms to maintain buoyancy and regulate nutrient uptake through specialized pores known as areolae (Cermeño et al.,2015). The elaborate patterns and nanoscale features of diatom frustules have fascinated researchers, leading to their exploration in biomaterial sciences and nanotechnology.

One of the defining characteristics of diatom frustules is their ability to withstand high pressures while remaining lightweight. This is due to the hierarchical organization of silica deposition, which creates a mechanically robust yet porous structure. Such an adaptation allows diatoms to survive in diverse environmental conditions while maintaining their photosynthetic efficiency (Figure 1).

2.2 Silica Biomineralization: The Formation of Diatom Frustules

The process of silica biomineralization in diatoms is a highly regulated biological mechanism that allows these organisms to construct their complex cell walls with remarkable precision (Figure 2). Silicic acid ($\text{Si}(\text{OH})_4$), the bioavailable form of silicon in aquatic environments, serves as the primary raw material for frustule formation. Diatoms take up silicic acid through specialized transporters located on their cell membranes, which actively regulate the intracellular concentration of silicon to optimize biomineralization. Once inside the cell, silicic acid is transported to a specialized organelle known as the silica deposition vesicle (SDV), where polymerization occurs to form amorphous silica. This vesicle plays a crucial role in dictating the final structure of the frustule by directing silica deposition along predefined nanoscale templates. The molecular mechanisms underlying this process involve silica-binding proteins known as silaffins and long-chain polyamines, which facilitate the controlled assembly of silica into highly ordered microstructures (Falkowski et al.,2004). During cell division, diatoms must replicate their silica frustules, a process that imposes constraints on their growth patterns. Each daughter cell inherits one half of the parent frustule and synthesizes a new, slightly smaller hypotheca to complete its structure. Over multiple generations, this results in a gradual reduction in cell size,

necessitating periodic size restoration through sexual reproduction. This unique reproductive strategy helps maintain genetic diversity while ensuring the continued structural integrity of diatom populations.

2.3 Silicon Uptake and Its Impact on the Silica Cycle

Diatoms are the dominant consumers of dissolved silica in marine and freshwater systems, making them central players in the global silica cycle. The uptake of silica by diatoms regulates its availability in aquatic environments, influencing the growth of other silica-dependent organisms such as sponges and radiolarians. The efficiency of silica uptake varies among diatom species, with some exhibiting highly specialized transport mechanisms that allow them to outcompete other phytoplankton in silicon-limited environments (Finkel et al.,2010).

In regions of high diatom productivity, such as coastal upwelling zones and polar oceans, massive diatom blooms lead to significant silica depletion in surface waters. Once diatoms die, their silica frustules either dissolve back into the water column or sink to the ocean floor, contributing to long-term silica sequestration in marine sediments. This sedimentary deposition plays a critical role in the geological cycling of silicon, as buried diatomaceous material eventually undergoes diagenesis, forming siliceous rocks such as diatomite and opal-rich deposits (Friedrichs et al.,2023). The dissolution of diatom frustules is influenced by environmental factors such as temperature, pH, and the presence of organic coatings that slow the rate of silica breakdown. In some cases, microbial communities play a role in silica remineralization by secreting enzymes that degrade the organic matrix associated with diatom frustules, facilitating their dissolution and recycling within the water column.

2.4 Ecological Advantages of Silica-Based Structures

The evolution of silica biomineralization in diatoms has conferred several ecological advantages, allowing them to thrive in a wide range of environments. Their rigid frustules provide effective protection against grazing by zooplankton and other predators, reducing mortality rates in planktonic communities. Additionally,

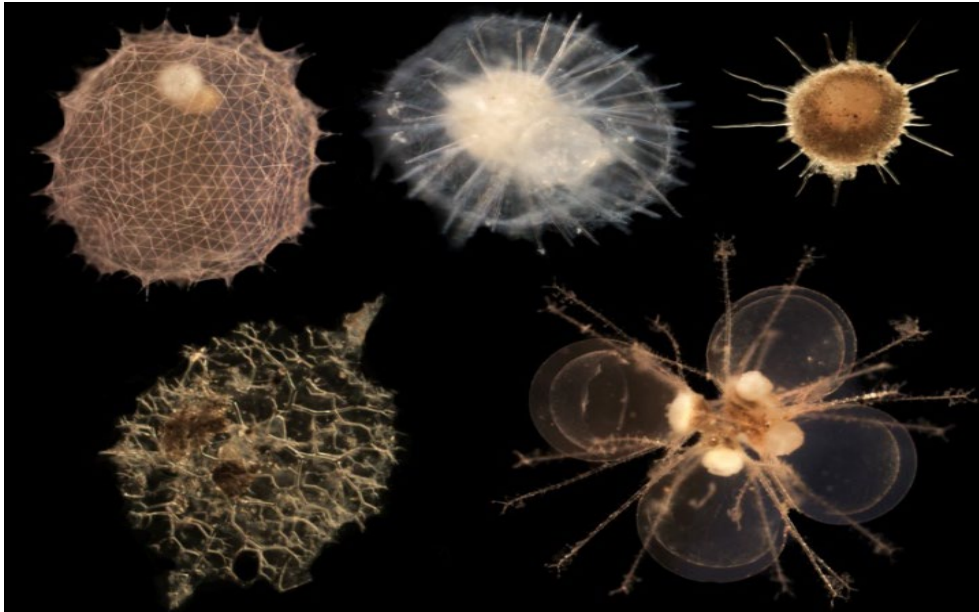


Figure 2. The Tiny Organisms That Transport Silica Across Earth's Oceans (courtesy of image from Leblanc et al.,2018)

the intricate surface structures of diatom frustules enhance light capture for photosynthesis, optimizing energy absorption in low-light conditions. Furthermore, the density of silica frustules affects diatom buoyancy, allowing them to adjust their position in the water column to optimize light and nutrient availability (Janech et al.,2006). Some diatom species possess vacuoles that regulate their buoyancy by modulating intracellular ion concentrations, enabling them to migrate vertically in response to environmental changes. Diatoms' ability to efficiently utilize silicon gives them a competitive advantage over non-siliceous phytoplankton in silicon-rich environments. This has significant implications for global nutrient cycling, as diatom-dominated ecosystems tend to exhibit higher rates of primary production and organic matter export. The role of diatoms in carbon sequestration further underscores their importance in regulating atmospheric CO₂ levels and mitigating climate change.

Diatoms are remarkable microorganisms whose ability to biomineralize silica has shaped global biogeochemical cycles for millions of years. Their intricate frustules serve multiple ecological functions, from structural protection to light optimization, while playing a critical role in the silica cycle. By efficiently taking up and depositing silica, diatoms influence nutrient availability, sediment formation, and long-term carbon storage in aquatic ecosystems (Karthick et al.,2009). Understanding the mechanisms behind silica biomineralization not only provides insights into diatom ecology but also offers potential applications in nanotechnology and materials science. As environmental conditions continue to change, further research is needed to assess how diatoms and the silica cycle will respond to anthropogenic influences and climate shifts.

3 Diatoms and Their Role in Marine Productivity and Nutrient Cycling

Diatoms are among the most productive photosynthetic organisms in aquatic ecosystems, contributing significantly to global primary production and biogeochemical cycles. Their role in marine productivity extends beyond carbon fixation, as they also drive essential nutrient cycles, including nitrogen, phosphorus, and silicon (Kröger et al.,2008). The high growth rates and rapid nutrient uptake capabilities of diatoms allow them to dominate phytoplankton communities, particularly in nutrient-rich environments. Their influence on marine food webs and biogeochemical cycling underscores their importance in sustaining oceanic life and regulating atmospheric carbon dioxide levels.

3.1 Diatoms as Primary Producers in Marine Ecosystems

As photosynthetic microorganisms, diatoms harness solar energy to convert inorganic carbon into organic matter through the process of photosynthesis. They account for approximately 40% of marine primary production and nearly 20% of the global carbon fixation, making them one of the most influential biological groups in carbon cycling. The efficiency of diatoms in capturing light and assimilating carbon is attributed to their specialized chloroplasts, which contain chlorophyll a, chlorophyll c, and fucoxanthin—a carotenoid pigment that enhances light absorption in blue and green wavelengths. Diatoms thrive in nutrient-rich environments, particularly in upwelling zones, estuaries, and coastal waters where deep-sea nutrients are brought to the surface (Lazarus et al.,2013). Their ability to respond rapidly to nutrient influxes allows them to form large seasonal blooms, which sustain marine food webs by providing a primary food source for zooplankton and higher trophic levels. The short generation times of diatoms, often ranging

from hours to a few days, enable them to outcompete other phytoplankton under favorable conditions.

Diatom blooms can have profound ecological consequences, influence the composition of marine ecosystems and affect trophic interactions. In regions such as the North Atlantic and the Southern Ocean, diatoms play a dominant role in supporting krill populations, which, in turn, sustain larger marine organisms such as fish, seabirds, and whales. The rapid turnover of diatoms also contributes to the biological carbon pump, a process that sequesters carbon in the deep ocean, thereby reducing atmospheric CO₂ levels.

3.2 The Role of Diatoms in the Nitrogen Cycle

Beyond carbon fixation, diatoms play a crucial role in the nitrogen cycle, particularly in nitrogen assimilation and the export of nitrogen-rich organic matter to deeper waters. Nitrogen is an essential macronutrient for diatom growth, and they can utilize various forms of nitrogen, including nitrate (NO₃⁻), ammonium (NH₄⁺), and, in some cases, nitrogen gas (N₂) through symbiotic relationships with nitrogen-fixing bacteria. Diatoms preferentially take up nitrate, the most abundant form of bioavailable nitrogen in the ocean, and incorporate it into amino acids, proteins, and other cellular components (Lopez et al., 2005). During periods of high productivity, diatom blooms can lead to rapid nitrogen depletion in surface waters, potentially limiting the growth of other phytoplankton species. However, as diatoms die and sink, their nitrogen-rich biomass is transported to deeper waters, where microbial decomposition releases nitrogen back into the environment, fueling the microbial loop and supporting deep-sea food webs. In some cases, diatoms engage in mutualistic interactions with nitrogen-fixing cyanobacteria, particularly in oligotrophic (low-nutrient) regions where bioavailable nitrogen is scarce. These associations allow diatoms to access nitrogen in environments where other phytoplankton struggle to survive, giving them a competitive advantage in open ocean ecosystems. Such symbiotic relationships play a significant role in global nitrogen cycling by introducing newly fixed nitrogen into marine food webs, ultimately supporting primary production in nitrogen-limited regions (Martin et al., 2000).

3.3 Diatoms and the Phosphorus Cycle

Phosphorus is another critical nutrient that influences diatom productivity, as it is required for ATP synthesis, nucleic acid production, and membrane formation. Diatoms acquire phosphorus primarily in the form of phosphate (PO₄³⁻), which is often a limiting factor in marine ecosystems. Unlike nitrogen, phosphorus does not have a significant atmospheric reservoir, making it more susceptible to depletion in surface waters due to biological uptake and sedimentation. Diatoms have evolved several strategies to cope with phosphorus limitation, including the ability to store excess phosphorus intracellularly when it is abundant (Medlin et al., 2016). This adaptation allows them to sustain growth

during periods of phosphorus scarcity by utilizing internal reserves. Additionally, diatoms can produce alkaline phosphatases, enzymes that break down organic phosphorus compounds into bioavailable phosphate, further enhancing their ability to compete for limited phosphorus resources. Phosphorus cycling in the ocean is closely linked to the biological carbon pump, as diatom-mediated phosphorus export to deep waters contributes to long-term nutrient sequestration. When diatoms sink to the ocean floor, their phosphorus content becomes buried in sediments, where it may remain locked away for millennia before being reintroduced into the water column through geological processes such as upwelling and weathering (Milligan et al., 2002). This dynamic interplay between biological uptake and sedimentation influences the overall availability of phosphorus in marine ecosystems, shaping diatom population dynamics and productivity.

3.4 Diatoms and the Silicon Cycle

The silica cycle, which is driven primarily by diatoms, regulates the availability of biogenic silica in marine environments. Diatoms require dissolved silica (Si(OH)₄) to construct their frustules, and their high silica uptake rates make them the dominant contributors to global silica deposition. Silica cycling is intricately linked to diatom population dynamics, as large diatom blooms can rapidly deplete dissolved silica concentrations in surface waters, limiting their own growth and creating ecological niches for non-siliceous phytoplankton. When diatoms die, their silica frustules either dissolve back into the water column or sink to the seafloor, contributing to the formation of siliceous sediments (Nunn et al., 2009). The dissolution of diatom silica is influenced by various environmental factors, including temperature, pH, and the presence of organic coatings that slow dissolution rates. In some regions, up to 80% of diatom silica is recycled within the upper ocean, sustaining continuous diatom growth, while the remaining fraction contributes to long-term silica burial in marine sediments.

4. Diatoms and Climate Regulation: Carbon Sequestration and Ocean Feedbacks

Diatoms play a crucial role in regulating Earth's climate through their involvement in the carbon cycle and their impact on oceanic feedback mechanisms. As dominant primary producers, diatoms contribute significantly to the uptake of atmospheric carbon dioxide (CO₂) through photosynthesis, subsequently influencing oceanic carbon storage and long-term climate stability. Their role in the biological carbon pump, combined with their rapid sinking rates and high organic carbon content, makes them essential players in carbon sequestration. Understanding how diatoms interact with climate feedback mechanisms is vital for predicting future climate changes and mitigating anthropogenic impacts on ocean ecosystems (Rabosky et al., 2009).

4.1 Diatoms and the Biological Carbon Pump

One of the most significant ways diatoms contribute to climate regulation is through the biological carbon pump, a process that transports carbon from the surface ocean to deep waters and sediments. By fixing CO₂ during photosynthesis, diatoms convert inorganic carbon into organic matter, which serves as a food source for higher trophic levels. When diatoms die, their organic-rich cells aggregate into marine snow, sinking rapidly to the deep ocean, where they become part of long-term carbon storage. Diatoms have a higher sinking efficiency than other phytoplankton due to their silica-based frustules, which increase their density. As a result, diatoms contribute disproportionately to carbon export compared to smaller phytoplankton like cyanobacteria or coccolithophores (Raven et al.,2009). Once in deep waters, diatom-derived organic matter is either decomposed by microbial activity or buried in sediments, where it can remain sequestered for centuries to millennia. This process effectively removes CO₂ from the atmosphere, reducing greenhouse gas concentrations and mitigating global warming.

The efficiency of the biological carbon pump is influenced by several factors, including diatom growth rates, nutrient availability, and oceanic circulation patterns. Upwelling regions, where deep, nutrient-rich waters reach the surface, often support massive diatom blooms that enhance carbon sequestration. Conversely, in oligotrophic regions with limited nutrients, diatom productivity is constrained, reducing carbon export efficiency (Shrestha et al.,2015). As climate change alters ocean circulation and nutrient distribution, diatom-mediated carbon sequestration patterns may shift, potentially affecting atmospheric CO₂ levels and climate stability.

4.2 Diatoms and the Solubility Pump: Enhancing CO₂ Absorption

In addition to the biological carbon pump, diatoms indirectly influence the solubility pump, a physical process that governs the ocean's capacity to absorb CO₂ from the atmosphere. The solubility pump operates based on temperature and gas solubility dynamics, with colder waters absorbing more CO₂ than warmer waters. Diatom-driven primary production contributes to CO₂ drawdown by reducing surface water CO₂ concentrations, thereby increasing the gradient between the atmosphere and the ocean (Vandevenne et al.,2013). Regions dominated by diatom blooms, such as the Southern Ocean and the North Pacific, serve as critical CO₂ sinks. These areas experience high rates of CO₂ absorption due to a combination of biological and physical processes. The organic carbon produced by diatoms eventually sinks to deep waters, further enhancing the ocean's capacity to store carbon. However, warming-induced stratification and reduced upwelling may limit nutrient supply to surface waters, potentially diminishing diatom productivity and the efficiency of CO₂ uptake.

4.3 Iron Fertilization and the Role of Diatoms in Climate Engineering

Diatoms' reliance on micronutrients like iron has led to significant interest in iron fertilization as a potential climate engineering strategy. Iron is a critical limiting nutrient in many oceanic regions, particularly the Southern Ocean, where primary production is constrained by low iron availability. Artificially adding iron to these waters has been proposed as a method to stimulate diatom blooms, thereby enhancing CO₂ drawdown and carbon sequestration. Experimental studies have demonstrated that iron enrichment can trigger large-scale diatom blooms, leading to increased carbon export to deep waters (Vardi et al.,2008). However, the long-term effectiveness and ecological consequences of iron fertilization remain uncertain. While short-term carbon sequestration may be enhanced, potential side effects include changes in food web dynamics, altered nitrogen and phosphorus cycling, and the risk of hypoxia in deeper waters due to increased microbial respiration. Additionally, some of the carbon sequestered through iron fertilization may be remineralized in the mid-water column rather than permanently stored in sediments. Despite these uncertainties, iron fertilization remains an area of active research, with potential implications for climate mitigation strategies. Understanding the response of diatoms to iron addition and their role in long-term carbon storage is essential for evaluating the feasibility of such geoengineering approaches (Wilhelm et al.,2006).

4.4 Ocean Acidification and Its Impact on Diatoms

Ocean acidification, driven by increased atmospheric CO₂ absorption, poses a growing threat to diatom populations and their role in carbon sequestration. As CO₂ dissolves in seawater, it reacts with water molecules to form carbonic acid, leading to a decrease in pH and alterations in carbonate chemistry. While some phytoplankton, such as coccolithophores, experience reduced calcification under acidic conditions, diatoms are generally considered more resilient due to their silica-based frustules (Andreozzi et al.,2019). However, ocean acidification can indirectly affect diatoms by altering nutrient availability and ecosystem interactions. Changes in carbonate chemistry may impact the solubility of silica, influencing diatom growth and frustule formation. Additionally, acidification can disrupt marine food webs, potentially altering grazing pressure on diatoms and their competitive interactions with other phytoplankton.

Recent studies suggest that some diatom species may experience increased growth rates under elevated CO₂ conditions due to enhanced photosynthetic efficiency. However, these benefits may be offset by other stressors, such as warming-induced stratification, reduced nutrient supply, and increased competition from non-siliceous phytoplankton (Armbrust et al.,2009). The long-term effects of ocean acidification on diatom populations and their role in carbon sequestration remain an area of active investigation.

4.5 Future Perspectives: The Role of Diatoms in a Changing Climate

As climate change accelerates, understanding the response of diatoms to environmental shifts is critical for predicting future carbon sequestration patterns. Rising sea surface temperatures, altered nutrient dynamics, and increased CO₂ concentrations will shape diatom community composition and productivity in complex ways. Some regions may experience enhanced diatom growth due to increased stratification and nutrient recycling, while others may see declines in diatom abundance due to nutrient limitations or shifts in competitive interactions (Arrieta et al.,2020). The potential for diatoms to mitigate climate change through carbon sequestration remains a key research area. Efforts to model future oceanic carbon fluxes must consider the intricate feedback mechanisms governing diatom productivity and their interactions with biogeochemical cycles. Additionally, conservation strategies aimed at preserving nutrient-rich upwelling zones and reducing anthropogenic stressors, such as pollution and overfishing, will be essential for maintaining healthy diatom populations and their role in climate regulation.

Diatoms are fundamental drivers of climate regulation through their role in carbon sequestration and oceanic feedback mechanisms (Austin et al.,2020). Their contribution to the biological carbon pump, solubility pump, and potential climate engineering strategies highlights their significance in mitigating global warming. However, the impacts of climate change, ocean acidification, and human activities on diatom populations remain uncertain. Future research must continue to explore the resilience of diatoms to environmental changes and their long-term contributions to oceanic carbon storage. Preserving diatom-rich ecosystems will be crucial for sustaining marine productivity and maintaining the delicate balance of the Earth's climate system.

5. Diatoms in Freshwater Ecosystems: Adaptations and Ecological Roles

While diatoms are often studied in the context of marine ecosystems, they are also dominant primary producers in freshwater environments, where they play essential roles in nutrient cycling, water quality maintenance, and ecological stability. Their ability to thrive in diverse freshwater habitats, from lakes and rivers to wetlands and reservoirs, highlights their remarkable adaptability. Freshwater diatoms contribute significantly to oxygen production, form the base of aquatic food webs, and serve as bioindicators for environmental monitoring. Understanding their ecological roles and adaptations provides insight into their importance in freshwater systems and how they respond to environmental changes (Bannon et al.,2017).

5.1 Adaptations of Diatoms to Freshwater Environments

Diatoms exhibit a range of adaptations that enable them to colonize diverse freshwater habitats. Their silica-based frustules provide structural support and protection against predation, while their

ability to regulate buoyancy allows them to optimize light absorption for photosynthesis. Unlike marine diatoms, many freshwater diatoms have evolved to thrive in environments with fluctuating nutrient availability, variable light conditions, and dynamic hydrological regimes. One key adaptation of freshwater diatoms is their ability to form resting stages, known as auxospores, which allow them to survive periods of unfavorable conditions such as desiccation, low temperatures, or nutrient depletion (Bowler et al.,2010). These resting spores can remain dormant for extended periods and resume growth when environmental conditions become favorable again. This survival strategy enables diatom populations to persist in ephemeral or seasonally variable water bodies, such as temporary ponds or floodplains.

Another significant adaptation is their diverse modes of attachment and movement. Many freshwater diatoms exhibit specialized structures, such as mucilage pads or stalks, that allow them to attach to submerged surfaces like rocks, aquatic plants, or sediments. Others, like the pennate diatoms, possess a raphe a slit-like structure that facilitates gliding motility using mucilage secretion. This movement enables them to navigate microhabitats, avoid unfavorable conditions, and access nutrients more efficiently (Conn et al.,2004).

5.2 Role of Diatoms in Freshwater Nutrient Cycling

Diatoms play a critical role in the cycling of essential nutrients, particularly carbon, nitrogen, phosphorus, and silica, within freshwater ecosystems. Through photosynthesis, they convert inorganic carbon into organic matter, which supports higher trophic levels, including zooplankton and fish. Their rapid growth rates and high biomass production make them primary contributors to freshwater primary productivity (Du et al.,2021). Silica cycling is particularly important in freshwater ecosystems, as diatoms require dissolved silica (SiO₂) to construct their frustules. When diatoms die, their silica-rich frustules settle into sediments, where they can either dissolve and re-enter the water column or become buried over time. This process regulates silica availability and influences the competitive dynamics between diatoms and other phytoplankton groups, such as green algae and cyanobacteria. In silica-limited environments, diatom populations may decline, leading to shifts in phytoplankton community composition and potential disruptions in ecosystem functioning (Du et al.,2019).

In addition to silica cycling, diatoms contribute to nitrogen and phosphorus dynamics. They uptake dissolved nitrogen (in the form of nitrate or ammonium) and phosphorus for growth, influencing nutrient availability and limiting the growth of competing phytoplankton species. In some cases, diatoms can help mitigate eutrophication by outcompeting harmful cyanobacteria for nutrients, reducing the likelihood of toxic algal blooms. However, in nutrient-rich conditions, excessive diatom growth can also

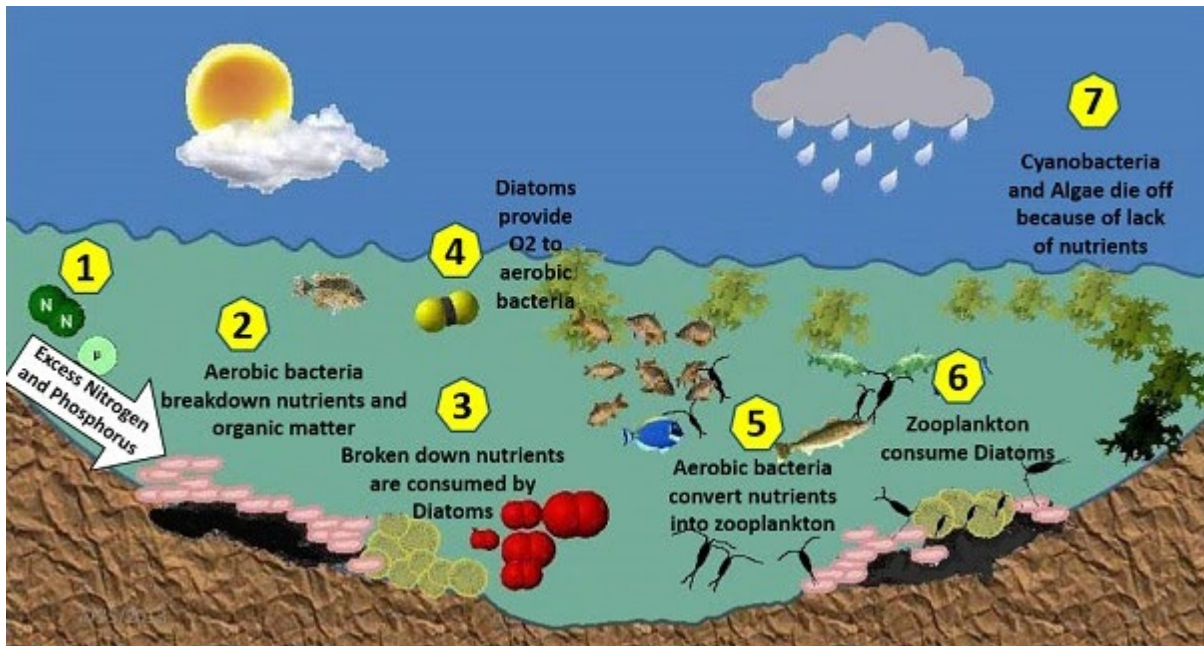


Figure 3. Process of diatoms to increase oxygen, create a healthier ecosystem, and eliminate harmful bacteria and algae (Antonelli et al., 2022)

contribute to seasonal algal blooms, which may lead to oxygen depletion when large amounts of organic matter decay.

5.3 Diatoms as Bioindicators of Water Quality

One of the most widely recognized ecological roles of freshwater diatoms is their use as bioindicators for water quality assessment. Because diatoms are highly sensitive to environmental changes, their species composition and abundance provide valuable insights into pollution levels, nutrient concentrations, pH variations, and habitat alterations (Durante et al., 2019). Diatoms respond predictably to changes in water chemistry, making them effective indicators of both natural and anthropogenic disturbances. For example, species such as *Achnanthes minutissimum* are associated with oligotrophic (low-nutrient) conditions, while species like *Nitzschia palea* thrive in eutrophic (high-nutrient) environments with elevated levels of nitrogen and phosphorus. By analyzing shifts in diatom assemblages over time, scientists can assess the impact of agricultural runoff, industrial pollution, or climate-induced changes on freshwater ecosystems (Falciatore et al., 2000).

Diatom-based water quality assessments are widely used in biomonitoring programs and regulatory frameworks. Many environmental agencies employ diatom indices, such as the Trophic Diatom Index (TDI) and the Pollution Sensitivity Index (PSI), to evaluate ecological health and track long-term trends in water quality. These indices integrate information on diatom species composition, pollution tolerance, and nutrient preferences to provide a standardized assessment of freshwater ecosystem conditions.

5.4 Impact of Climate Change on Freshwater Diatoms

Climate change is altering freshwater ecosystems worldwide, with significant implications for diatom populations and their ecological functions. Rising temperatures, changes in precipitation patterns, and increased frequency of extreme weather events are influencing diatom distribution, growth dynamics, and community composition. One major impact of climate change is the alteration of seasonal diatom blooms. In many temperate and polar regions, diatom productivity follows a distinct seasonal cycle, with peak growth occurring in spring and autumn when light and nutrient conditions are optimal (Fanesi et al., 2014). However, warming-induced shifts in stratification patterns and nutrient availability may disrupt these seasonal cycles, leading to earlier or more prolonged diatom blooms. Such changes can have cascading effects on aquatic food webs, as diatoms serve as a crucial food source for zooplankton and higher consumers.

Additionally, climate change is expected to intensify eutrophication in freshwater ecosystems, potentially favoring cyanobacteria over diatoms. Warmer temperatures, altered hydrological regimes, and increased nutrient loading from human activities may create conditions that promote cyanobacterial dominance, thereby reducing diatom biodiversity and disrupting ecosystem balance (Flynn et al., 2000). This shift could have negative consequences for water quality, as cyanobacterial blooms are often associated with the production of harmful toxins and oxygen depletion. Despite these challenges, some diatom species may exhibit resilience to climate change by adapting to new environmental conditions (Figure 3). Understanding the mechanisms driving diatom responses to

warming, altered flow regimes, and nutrient fluctuations is essential for predicting future changes in freshwater ecosystems and developing effective conservation strategies.

6. Diatoms in Human Applications: Biotechnology, Industry, and Environmental Solutions

Diatoms have fascinated scientists and industries alike due to their unique structural properties, biochemical composition, and ecological significance. Their intricate silica frustules, high lipid content, and ability to perform efficient photosynthesis have led to their application in diverse fields, including biotechnology, nanotechnology, environmental remediation, and industry. As research continues to uncover new possibilities, diatoms are emerging as valuable resources in sustainable solutions for energy production, water purification, and medical advancements (Friedrichs et al., 2012).

6.1 Biotechnological Applications of Diatoms

The remarkable structural and chemical properties of diatoms make them prime candidates for biotechnology. One of the most promising applications is in biofuel production. Diatoms are capable of accumulating high amounts of lipids, particularly under nutrient-limited conditions, making them an attractive source for biodiesel production. Compared to traditional biofuel sources such as soybean or palm oil, diatoms offer faster growth rates, higher biomass productivity, and the ability to grow in non-arable land, reducing competition with food crops. Additionally, diatoms have been explored for their potential in biophotovoltaics—biological solar cells that harness their photosynthetic efficiency to generate electrical energy (Gemmell et al., 2016). Research has demonstrated that diatom-based systems can convert sunlight into energy with remarkable efficiency, offering a sustainable and renewable source of power. This technology has potential applications in low-energy environments, wearable electronics, and remote sensing devices.

In medicine, diatoms are being studied for drug delivery systems. Their silica-based frustules provide a biocompatible and biodegradable framework for encapsulating pharmaceuticals. Scientists have successfully engineered diatom frustules to carry targeted drug molecules, allowing for controlled release in specific parts of the body (Giordano et al., 2005). This method improves drug stability, enhances bioavailability, and reduces side effects, making diatoms a promising tool in nanomedicine.

6.2 Industrial Uses of Diatomaceous Earth

Diatomaceous earth (DE), a naturally occurring sedimentary rock composed of fossilized diatom remains, has been utilized in various industrial applications for over a century. Due to its high porosity, low density, and abrasive properties, DE is widely used as a filtration aid, abrasive, absorbent, and insulating material (Hamano et al., 2021). One of the most common industrial applications of DE is in filtration, particularly in water purification, beverage production,

and pharmaceutical processing. The porous structure of diatom frustules makes DE an efficient medium for filtering out impurities, bacteria, and suspended solids from liquids. It is extensively used in beer and wine production to clarify beverages without affecting flavor.

Another significant use of DE is in pest control. The fine, abrasive particles of diatomaceous earth can penetrate the exoskeletons of insects, leading to dehydration and death. As a non-toxic, chemical-free alternative to synthetic pesticides, DE is widely used in organic farming and household pest management. DE is also employed in the production of insulation materials, particularly in high-temperature environments such as furnaces and kilns (Hammer et al., 2001). Its ability to withstand extreme temperatures while maintaining lightweight properties makes it a valuable component in industrial insulation and fireproofing materials.

6.3 Diatoms in Environmental Remediation

Beyond industrial and biotechnological applications, diatoms have been recognized for their role in environmental cleanup and sustainability. One of the most promising areas is their application in bioremediation—using living organisms to remove pollutants from the environment. Diatoms have demonstrated a remarkable ability to absorb heavy metals such as lead, mercury, and cadmium from contaminated water bodies. Their silica frustules provide an effective surface for metal adsorption, making them useful in wastewater treatment. Research has shown that engineered diatoms can be used as biosorbents to capture toxic pollutants from industrial effluents, reducing environmental hazards and improving water quality (Hervé et al., 2012).

In addition to heavy metal remediation, diatoms play a crucial role in carbon sequestration. Their photosynthetic activity contributes significantly to the global carbon cycle by capturing atmospheric CO₂ and converting it into organic matter. Large-scale diatom blooms in oceans and freshwater systems act as carbon sinks, helping mitigate the effects of climate change by reducing greenhouse gas concentrations. Scientists are exploring ways to enhance diatom-based carbon sequestration through artificial upwelling and nutrient fertilization, potentially creating a natural method for carbon dioxide removal from the atmosphere (Hildebrand et al., 2018).

Diatoms have also been proposed as a solution for oil spill remediation. Certain diatom species can break down hydrocarbons and organic pollutants, accelerating the degradation of oil spills in marine and freshwater environments. When combined with bioengineered bacteria, diatoms can enhance biodegradation rates, making them a viable alternative to chemical dispersants.

6.4 Diatoms and Sustainable Agriculture

Diatoms contribute to sustainable agriculture in multiple ways, particularly through soil enrichment, organic fertilizers, and pest control. Diatomaceous earth is widely used as a natural soil

conditioner, improving aeration, water retention, and nutrient availability (Jin et al. 2006). The silica content in DE enhances plant structural integrity, making crops more resistant to pests and diseases. Diatom-based biofertilizers are gaining attention as an eco-friendly alternative to synthetic fertilizers. By incorporating diatoms into soil amendments, farmers can promote plant growth, enhance microbial diversity, and reduce dependency on chemical fertilizers. Studies have shown that diatom applications can improve crop yield, enhance root development, and increase resistance to environmental stressors, such as drought and salinity (Laurenceau et al., 2020). Furthermore, the use of diatom-based pest control methods aligns with the principles of sustainable and organic farming. Unlike chemical pesticides, diatomaceous earth does not leave harmful residues in the soil or pose risks to non-target organisms. Its effectiveness in controlling agricultural pests such as aphids, mites, and weevils makes it a valuable tool for integrated pest management.

6.5 Future Perspectives and Challenges

Despite their immense potential, the large-scale application of diatoms in biotechnology and industry faces several challenges. Cultivating diatoms for biofuel production, for example, requires optimization of growth conditions, efficient harvesting techniques, and cost-effective lipid extraction methods. While diatoms offer high lipid yields, economic and technological barriers still limit their commercial viability (Lavoie et al., 2020; Antonelli et al., 2022). Similarly, the use of diatoms in environmental remediation must be carefully managed to prevent unintended ecological consequences. While diatom blooms can enhance carbon sequestration, excessive artificial fertilization may lead to harmful algal blooms that disrupt aquatic ecosystems (Lavoie et al., 2016). Striking a balance between harnessing diatoms' benefits and preserving ecological stability remains a critical research priority. Looking ahead, advances in genetic engineering and synthetic biology hold promise for enhancing diatom-based applications. Researchers are developing genetically modified diatoms with improved lipid production, enhanced metal absorption capacity, and tailored biosilica structures for nanotechnology applications. These innovations could unlock new possibilities in sustainable energy, environmental protection, and medical research.

7. Conclusion

Diatoms are vital to both natural ecosystems and human innovation. Their role in regulating biogeochemical cycles, particularly the silica and carbon cycles, supports aquatic productivity and global climate stability. At the same time, their structural and biochemical properties have opened new frontiers in biotechnology, industry, and environmental remediation. As research advances, diatoms offer promising solutions for renewable energy, pollution control, and nanotechnology. However, realizing

their full potential requires a careful balance between technological exploitation and ecological preservation. By responsibly leveraging their capabilities, diatoms can help shape a more sustainable and resilient future for the planet.

Author contributions

P.B. conceived, designed, and conducted the study, analyzed the data, and prepared the manuscript. The author read and approved the final version.

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Competing financial interests

The authors have no conflict of interest.

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