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Symbiotic and Antagonistic Relationships between Microalgae and Environmental Microorganisms

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Abstract There is a complex interaction between microalgae and environmental microorganisms, including two major categories: mutually beneficial symbiosis and hostile antagonism. This interaction not only affects the functions of aquatic ecosystems, but also has great significance for applications such as biomass energy production and sewage treatment. This study outlines the biological characteristics of microalgae and the diversity of environmental microbial communities, elaborates on the symbiotic mechanisms of nutrient complementarity, matter exchange, signaling, etc. of microalgae-microbial interaction, as well as hostile effects such as nutritional competition, allelosensitivity inhibition, viral parasitism and predation. Typical cases such as symbiosis between cyanobacteria and nitrogen-fixing bacteria, co-culture of microalgae-heterotrophic bacteria to improve biofuel yield, and disintegration of algae blooms by viruses, revealing the far-reaching impact of microalgae-microbial interaction on community diversity, water bloom succession and global carbon, nitrogen and phosphorus cycle. On this basis, we look forward to the future research directions in molecular mechanism analysis, multiomics technology application and ecological engineering regulation.

Keywords Microalgae; Environmental microorganisms; Symbiosis; Antagonism; Algae interaction

1 Introduction

Microalgae are a type of tiny algae that can perform photosynthesis. They are widely distributed in the ocean, freshwater and wetland environments. Their photosynthetic carbon sequestration occupies an important position in the global primary productivity. In nature, a large number of microorganisms such as bacteria, fungi, viruses, and protozoa are found around microalgae, which together constitute the so-called "algaein circle" microenvironment (Zhou et al., 2014; Kuhlisch et al., 2023). The interaction relationship between these microalgae and environmental microorganisms can be roughly divided into two aspects: mutually beneficial symbiotic relationship and mutually inhibited hostile relationship.

The symbiotic relationship between microalgae and microorganisms is of great significance to maintaining the function and balance of aquatic ecosystems. On the one hand, microalgae fix CO_2 through photosynthesis and release oxygen and organic carbon sources to provide energy and nutrients to heterotrophic microorganisms; on the other hand, bacteria and other microorganisms feed back to microalgae by decomposing organic matter, regenerating nutrients or synthesizing vitamins to promote the growth of algae. This symbiosis mechanism of nutritional complementarity not only improves the community's utilization efficiency of resources, but also shows application value in the fields of sewage treatment, bioenergy, etc. (Morris et al., 2022).

At the same time, there are also hostile effects such as competition and antagonism between microalgae and microorganisms. Eutrophication of water bodies often leads to overpropagation of certain microalgae to form "water blooms", which leads to changes in bacterial community structure and nutrient competition. Some bacteria secrete algal soluble substances to inhibit algae growth, while viral infection can lead to lysis of algae cells and accelerate algae bloom decay (Lin et al., 2024). These hostile effects not only affect algae population dynamics, but also may cause ecosystem dysfunction, such as water bloom disintegration, resulting in deterioration of water quality and a decrease in biodiversity.

Given the importance of interaction between microalgae and environmental microorganisms in terms of ecology and application, this study reviews the main types and mechanisms of symbiosis and hostility relationships between the two; introduces the basic characteristics of microalgae and environmental microorganisms, and then analyzes the symbiosis modes such as nutritional complementarity and signaling, and explains them in combination with typical cases. Finally, the ecological significance of microalgae-microbial interaction is summarized and future research directions are looked forward.

2 Basic Characteristics of Microalgae and Environmental Microorganisms

2.1 Biological characteristics and ecological functions of microalgae

Microalgae generally refer to single-cell or population algae that can perform photosynthesis, including prokaryotic cyanobacteria and eukaryotic green algae, diatoms, dinoflagellates and other groups. For example, Spirulina, Chlorella, Microcystis, etc. are all common microalgae representatives. Microalgae usually have the characteristics of rapid growth and high photosynthetic efficiency, and can reproduce in large quantities under suitable conditions (Sarıtaş et al., 2024). Ecologically, microalgae are the basic primary producers of aquatic food webs, and undertake the role of converting solar energy into chemical energy and fixing CO_2, providing organic matter and oxygen to the entire aquatic ecosystem (Li et al., 2022). It is estimated that about half of the world's atmospheric oxygen comes from the photosynthesis of phytoplankton microalgae in the ocean, and its carbon sink has an important impact on climate regulation. In addition, different microalgae can also produce a variety of metabolites, such as proteins, polyunsaturated fatty acids and pigments, which are of development value in the fields of aquaculture, food and medicine.

2.2 Diversity and distribution pattern of environmental microbial communities

Environmental microorganisms generally refer to microorganisms such as bacteria, archaea, fungi, viruses and protozoa distributed in various environments, with extremely diverse species and functions. Take water as an example. Each milliliter of seawater contains millions of bacteria and viral particles. These microorganisms play a key role in decomposing organic matter, circulating nutrients, and regulating ecosystems. The composition of environmental microbial communities varies according to environmental conditions: in nutrient-rich water bodies, heterotrophic bacteria often dominate and utilize organic matter released by algae; and in clean, poor nutrient water bodies, autotrophic archaea and nitrogen-fixing bacteria also occupy a certain position. It is worth noting that many water microorganisms have close spatial connections with algae. For example, the "algae" area around microalgae cells converges specific bacterial communities, which are usually more diverse than the surrounding water phase. These algal microorganisms gather near algae with the help of motility such as flagella to form a stable microecological structure, providing a place for algae interactions (Garcia et al., 2022).

2.3 Theoretical basis of microalgae-microbial interaction

The interaction relationship between microalgae and microorganisms is based on long-term co-evolution, reflecting the dual characteristics of synergy and antagonism. On the one hand, the "reciprocity and symbiosis" theory believes that different populations maximize resource utilization through division of labor and cooperation. For example, many green algae themselves cannot synthesize essential nutrients such as vitamin B12 and must rely on symbiotic bacteria to provide this vitamin to maintain growth. While bacteria obtain organic carbon sources from algae, they synthesize vitamins for algae. This mutually beneficial relationship is called the "nutritional complementary symbiosis mechanism" (Schlogelhofer et al., 2019). On the other hand, ecological competition theory points out that competitive exclusion will occur during the limited time of resources. Microalgae and bacteria may compete for nutrients such as nitrogen and phosphorus in water, which will inhibit the growth of the other party when one party reproduces in large quantities. In addition, the "group sensing" theory emphasizes the role of information exchange in interaction. Bacteria can release signal molecules such as N-acylhoserine lactone, perceive population density and regulate the production of algae-soluble substances. Algae are also able to secrete chemically induced substances that interfere with bacterial signals, thereby mitigating adverse effects (Figure 1) (Weiland-Bräuer, 2021; Srinivas et al., 2022).

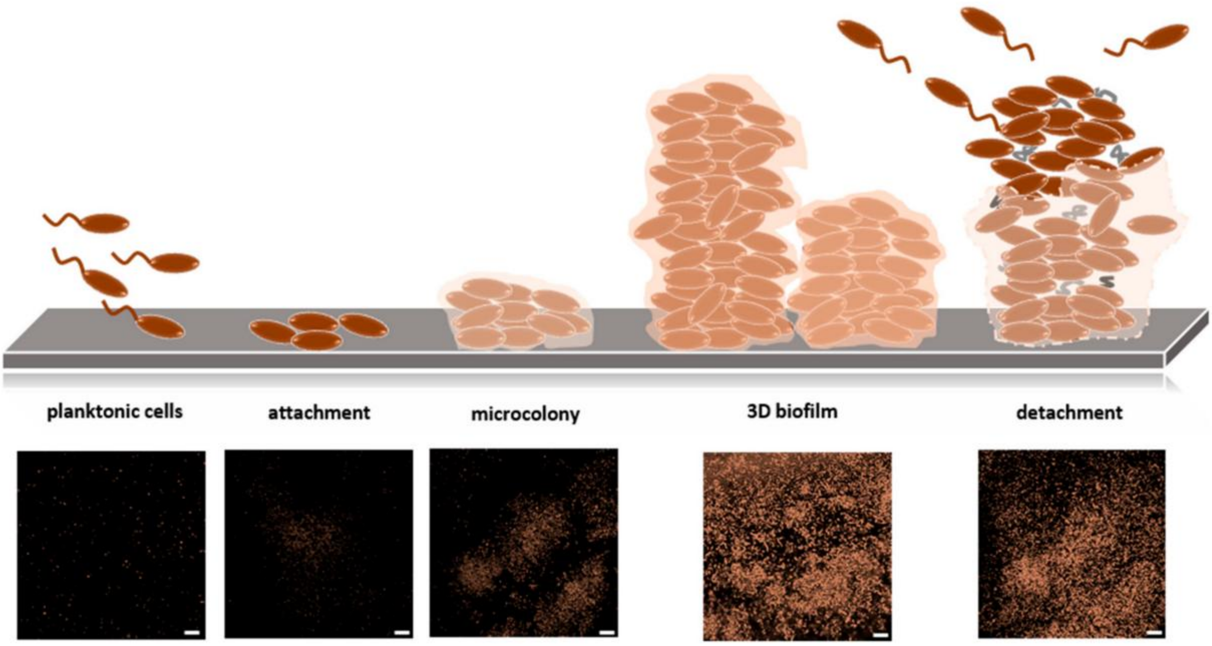

Figure 1 Biofilm development. Free-swimming bacteria initially attach to a solid surface, and colonizing bacteria further form structured aggregates called microcolonies. Biofilms are composed of numerous microcolonies, which are encased in an extracellular polymeric matrix. Biofilms permanently undergo composition/decomposition. Confocal Laser Scanning Micrographs of *Klebsiella oxytoca* M5aI biofilm formation (Adopted from Weiland-Bräuer, 2021)

3 Main Types of Symbiotic Relationships

3.1 Nutritional complementarity and substance exchange

Nutritional complementarity is one of the most basic types of relationships in the symbiosis between microalgae and microorganisms. Photosynthesis allows microalgae to convert inorganic carbon into organic carbohydrates and release oxygen, providing energy and oxygen sources for surrounding heterotrophic microorganisms; while microorganisms use organic matter and metabolic waste excreted by microalgae to feed back nutrients such as inorganic nitrogen and phosphorus to the microalgae through mineralization and regeneration. For example, some nitrogen fixation bacteria can convert N_2 in the atmosphere into ammonium salts or amino acids available to microalgae, thereby supplementing the nitrogen source in algae culture. For example, iron carriers secreted by certain bacteria help to improve the uptake rate of trace iron by microalgae, promote the synthesis of photosynthesis enzymes, and significantly accelerate the growth of algae cells. In addition, vitamin reciprocity is also a common way of nutritional complementarity - about half of microalgae cannot synthesize the B vitamins independently, and symbiotic bacteria need to provide cofactors such as vitamin B12, while bacteria obtain photosynthetic products from algae to meet their own carbon source needs. Through these substance exchanges, microalgae and microorganisms achieve resource recycling and mutually beneficial symbiosis (Li, 2024).

3.2 Microalgae - mutually beneficial symbiosis model of bacteria

Various mutually beneficial symbiosis patterns have been found between microalgae and bacteria, with diverse mechanisms but the results are reflected in the mutual promotion of growth or function of both parties. A typical model is that in wastewater biological treatment systems, co-culture of algae can simultaneously remove contaminants in water and increase microalgae biomass production. Studies have shown that compared with monoalgae or monoglycculture, the algae-bacterial symbiosis system has a higher efficiency in removing nutrients such as nitrogen and phosphorus, and the growth rate and oil accumulation of microalgae have increased significantly (Hu et al., 2019; Dai and Wang, 2023). For example, in urban sewage treatment, constructing a particle symbiosis of Chlorella and activated sludge bacteria can increase the removal rate of ammonia nitrogen and phosphate to a level that is difficult to reach in the pure bacteria system, while reducing CO_2 emissions and residual sludge yields (Zhang et al., 2021). In the field of bioenergy, co-cultivating beneficial bacteria can also improve the oil production performance of microalgae. In experiments, Chlorella and Pantoea were co-cultured at a ratio of 1:5. After 8 days, the biomass and oil content of algae cells increased significantly, which were significantly higher than those of the culture group alone. Many algae-promoting bacteria can also secrete auxin (IAA), vitamins and signaling molecules to stimulate algae cell division or release dormancy, thereby further enhancing the growth rate and physiological activity of microalgae. By screening the dominant symbiotic bacteria and optimizing the proportion of algae inoculation, the mutually beneficial symbiotic effects can be maximized and the enhancement of microalgae reproduction and metabolites output can be achieved.

3.3 Microalgae - fungal symbionts and complex ecosystems

The symbiotic relationship between microalgae and fungi is also of great ecological significance. The most famous example is lichen - a symbiont composed of green algae or cyanobacteria and fungi. In lichens, microalgae provide carbohydrates for fungi, and fungi provide shelter and moisture nutrients for algal cells. Through this close cooperation, both parties can survive and reproduce in extreme environments. In comparison, there are slightly fewer studies on microalgae-fungal symbiosis in aquatic environments, but in recent years, they have gradually attracted attention in ecological engineering. Because of its developed mycelium, filamentous fungi can adhere and bind to microalgae to form particles, causing microalgae to spontaneously flocculate and settle down from the culture medium. This fungi-assisted bioflocculation technique significantly reduces the harvest cost of microalgae biomass. For example, co-culture of *Aspergillus fumigatus* with Chlorella can form stable large particles, which can effectively remove organic pollutants and nutrients from wastewater after settlement. Some aquatic fungi can also secrete enzymes to degrade polymers such as algae cell walls and polysaccharides, and work with microalgae to accelerate the circulation of organic matter. In a complex complex ecosystem, microalgae, bacteria, fungi and other protophytes can jointly form a multi-symbiotic network, and various organisms maintain the stability and productivity of the system through the exchange of substances and information (Wrede et al., 2014; Talukder et al., 2021). This type of composite system has shown good application prospects in sewage treatment, wetland restoration, etc.

4 The Relationship Between Enemy and Antagonism

4.1 Nutrition and niche competition

When environmental resources are limited, competition occurs between microalgae and microorganisms, thereby inhibiting each other's growth. This competition between nutrients and niches is particularly evident in the succession of algae blooms in eutrophied water bodies. When microalgae reproduce in large quantities, they consume essential nutrients such as nitrogen and phosphorus in the water, which makes bacteria and other algae limited by lack of nutrients; on the contrary, when heterotrophic bacteria overproliferate, they will also inhibit the photosynthesis and reproduction of algae by competing for resources such as organic carbon sources and oxygen. There is also competition for the occupation of habitats by different populations (Wu and Wang, 2024). For example, phytoplankton and attached bacteria may compete for light conditions in the water column: algae need to absorb light energy, while excessive bacterial reproduction will increase the turbidity of the water body, weaken the depth of light penetration, thereby indirectly inhibiting algae photosynthesis. Similarly, the consumption of large amounts of dissolved oxygen by microorganisms can also threaten the survival of algae (Sörenson et al., 2020). Competition between nutrition and ecological niches often leads to the replacement of community dominant species, causing a dynamic balance between the number of microalgae and microorganisms to rise and fall. By regulating the supply of external nutrients, this competitive relationship can be intervened to a certain extent, thereby achieving the purpose of controlling water blooms or regulating community structure.

4.2 Antagonistic substances and allelopathic effects

In addition to competing for resources, microalgae and microorganisms also inhibit each other by releasing chemicals, the so-called allelopathic or antagonistic effect. On the one hand, many aquatic bacteria have the ability to produce algae-soluble substances. Such metabolites include proteases, organic acids, polypeptide toxins, etc., which can damage the structure of algae cells or disrupt their physiological functions, ultimately leading to the lysis and death of algae cells. For example, Rosobacteria marine secretes active molecules to exert a strong lytic effect on dinoflagellate cells, which can accelerate the red tide's regression (Wang and Coyne, 2022). For example, bacteria of *Pseudomonas* can produce reactive oxygen species such as hydrogen peroxide, causing algae cells to suffer oxidative stress and apoptosis. On the other hand, microalgae can also release allelopathic substances that are unfavorable to bacteria or other algae. Some cyanobacteria produce algal toxins such as microcystis toxins, which not only poison zooplankton, but also inhibit the growth of competing algae (Zak and Kosakowska, 2016). For example, compounds such as phenolic acid secreted by large aquatic plants can inhibit the photosynthesis and respiration of cyanobacteria, thereby curbing the excessive proliferation of harmful algae to a certain extent.

4.3 Parasitic and predation of microalgae by viruses, fungi and protozoa

Microalgae not only face bacterial competition and chemical inhibition, but are also often directly attacked by viruses, fungi and protozoa. Aquatic viruses are one of the largest biological entities in the aquatic ecosystem, with as many as tens of millions of virus particles per milliliter of seawater, a considerable number of which are hosted by algae. These algae phage viruses usually specifically infect specific algae species, completing life history by replicating and lysing the host in algae cells, resulting in the disintegration and subsidence of algae blooms in a short period of time. For example, there have been many outbreaks of *Aureococcus anophagefferens* on the east coast of the United States. Research has found that a specific algae phage virus infected a large number of brown algae cells during the peak of the bloom, causing its population to collapse rapidly within a few days (Yu et al., 2023). These examples show that sudden outbreaks of viruses can end algae blooms through top-level killing mechanisms, and have a severe impact on local ecosystems. On the other hand, parasites of aquatic fungi also play a role in the regulation of algae populations. For example, fungi such as gypsum chytrium parasitize in diatoms, seizing algae cell nutrients and causing host death. In addition, miniature predators such as ciliates, meat-pods and rotifers feed on algae, and each individual ciliate can swallow tens of thousands of algae cells every day, thus forming a strong top control over algae populations (Bergman et al., 2024). Zooplankton predation of dominant algae species can effectively inhibit their overproliferation, so it is often regarded as a biological control method in water quality control. The dynamic game between microalgae-virus-predators jointly determines the rise and fall of algae populations, and has a profound impact on the material circulation and energy flow of water bodies.

5 Molecular and Ecological Mechanisms of Interaction

5.1 Signaling and group sensing mechanism

The interaction between microalgae and microorganisms is not only reflected in nutrient exchange, but also regulates each other's behavior through delicate signaling processes. The "Quorum Sensing" (QS) mechanism of bacteria is a key link: when the bacterial density reaches a certain level, the concentration of self-induced signal molecules it secretes increases, which triggers the expression of related genes after being sensed by the bacteria. In the algal microenvironment, QS signaling can affect the physiological activity of algae. On the other hand, microalgae will also use signal molecules for "reverse communication". *Chlamydomonas* can secrete lactonease to degrade bacteria's AHL signals, thereby interfering with the bacteria's mass sensing process (Dow, 2021). In addition, metabolites such as polysaccharides and pigments released by microalgae may also act as information media to attract or reject specific microorganisms to attach. Through complex signaling networks, microalgae and microorganisms can perceive each other's existence and regulate their own physiology, achieving dynamic control of the interaction relationship.

5.2 Interaction patterns revealed by genomics and multiomics

With the development of high-throughput sequencing and multiomics technologies, people have gained a deeper understanding of the molecular mechanisms of microalgae-microbial interactions. Genomics studies show that many microalgae and bacteria have undergone gene complementarity and functional differentiation in long-term co-evolution. For example, in a symbiotic system of a bialgae, the genome of the endosymbiotic nitrogen fixation bacteria was greatly simplified, and some carbon metabolism pathways were lost. The host algae lacked the nitrogen fixase gene, but the functions of both parties were just complementary, allowing the symbionts to fix carbon and nitrogen at the same time (Kimotho and Maina, 2023). Transcriptome and proteome analyses further reveal dynamic patterns of gene expression between both parties during interaction. Experiments show that when Chlorella co-cultured with probiotic bacteria, photosynthesis and carbon sequestration related genes in algae cells are upregulated, while bacteria enhance organic decomposition utilization and vitamin synthesis pathways (Wirth et al., 2023). Metagenomic research also found that there are a large number of unique metabolic enzymes and pathway genes in algae microorganisms, indicating that the algae flora has evolved special functions in order to adapt to the ecological niche that coexist with algae. By integrating multiomics data, researchers are gradually building a systematic model of microalgae-microbial interaction to analyze the operating mechanism of symbiotic or antagonistic relationship as a whole.

5.3 Coupling relationship between metabolic network and carbon and nitrogen cycle

The interaction between microalgae and microorganisms directly affects the local, even global carbon, nitrogen and phosphorus circulation processes at the ecological level. Photosynthetic microalgae immobilize inorganic carbon and release a portion of it into water in the form of dissolved organic matter (DOM), which heterotrophic bacteria use and decompose carbon respiration into CO_2. It is estimated that bacteria in the ocean consume 25%~50% of the carbon fixed by algae, reflecting the important feedback effect of microbial communities on the carbon cycle (Kuypers et al., 2018). At the same time, the decomposition of bacteria turns organic nitrogen and phosphorus in algae biomass into inorganic states, and is absorbed and utilized by algae again. A newly discovered phytoplankton diatom is symbiotic with nitrogen-fixing rhizobia, whose fixed nitrogen is directly supplied to the host algae for use, and is believed to fill the nitrogen deficiency in the oceanic seas (Wang et al., 2024). In environments such as estuaries, the oxygen released by photosynthesis of algae promotes nitrifying bacteria to oxidize ammonium to nitrates, while heterotrophic denitrifying bacteria then reduce nitrates to nitrogen to escape from the water, forming a nitrogen circulation pathway connected by algae-aerobic bacteria and anaerobic bacteria.

6 Case Analysis

6.1 Typical symbiotic system between cyanobacteria and nitrogen-fixing bacteria

In the oceanic oceans, the symbiosis between plankton diatoms and nitrogen-fixing microorganisms is widely present. Traditionally, the main nitrogen fixing organism in the ocean is cyanobacteria, but in recent years, some non-cyanobacterial nitrogen fixing bacteria have also been found to symbiotically with algae to fix nitrogen. A large-scale marine diatom symbiotic with filamentous cyanobacteria mycelium Richelia, which can contribute a considerable proportion of nitrogen input in the tropical Pacific (Villareal, 2020). What is even more remarkable is the latest research finding that a heterotrophic bacteria from the order Rhizobiales can live in single-cell diatoms and directly provide nitrogen to the host through nitrogen fixation. This discovery expands people's understanding of the nitrogen fixation pathways in marine organisms, indicating that in addition to cyanobacteria, certain conventional bacteria can also participate in the marine nitrogen cycle through symbiosis with algae (Figure 2) (Tschitschko et al., 2024).

6.2 Case of co-culture of microalgae and heterotrophic bacteria to increase biofuel yield

Algae coculture technology shows great potential to increase yield in the field of biofuels. Co-culture of oil-producing microalgae with specific heterotrophic bacteria under laboratory conditions can significantly improve microalgae biomass and oil production. After Chlorella symbiotic with a Pantoea pineapple strain, its algae cell dry weight and oil content were significantly higher than those in the culture group alone (Zhang et al., 2023). In larger-scale experiments, the algae symbiotic system also showed excellent performance: When dealing with urban sewage, the microalgae-bacterial sludge process reported by Guo et al. (2021) not only efficiently removes pollutants such as nitrogen and phosphorus in the water, but also simultaneously produces considerable microalgae biomass, and its carbon conversion efficiency and oil production potential are better than traditional methods. These cases prove that by screening and introducing probiotic bacteria, the oil production efficiency of the microalgae culture system can be significantly improved, providing a more economical and feasible way to the production of new energy such as biodiesel.

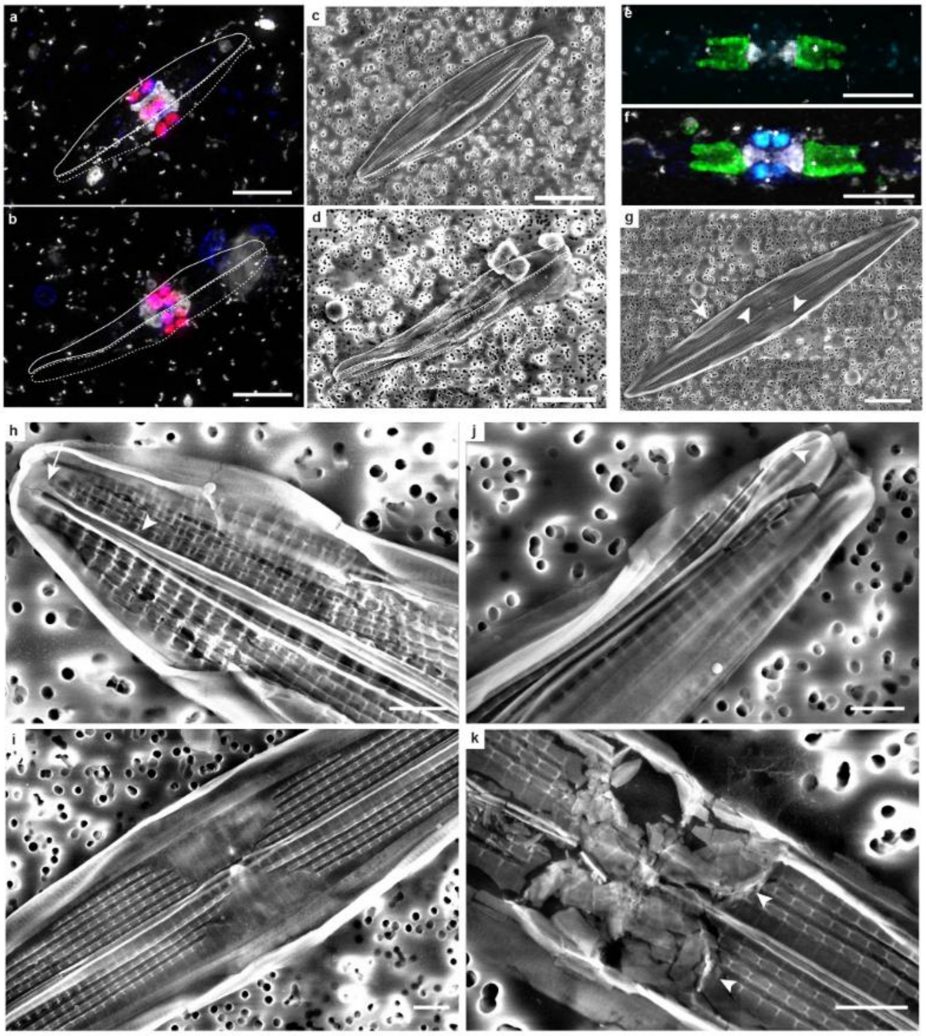

Figure 2 Microscopic characterization of '*Candidatus* Tectiglobus diatomicola'-*Haslea* symbioses (Adopted from Tschitschko et al., 2024)

6.3 Examples of ecosystem disintegration caused by algae blooms and virus outbreaks

Flora is an ecological phenomenon caused by excessive algae reproduction, and its growth and decline are often strongly affected by viruses. When environmental conditions change or algae phage viruses appear in large quantities, algae bloom populations may collapse and subside in a short period of time. For example, there have been many large-scale outbreaks of *Aureococcus anophagefferens* on the east coast of the United States. Research has found that a specific algae phage virus infected a large number of brown algae cells during the peak of the bloom, causing its population to collapse rapidly within a few days (Frada and Vardi, 2015). It can be seen that the sudden outbreak of the virus can end algae through the top-level killing mechanism and have a severe impact on the local ecosystem. In freshwater environments, parasites of fungi and predation by protozoa also significantly influence algae population dynamics. For example, the aquatic fungus gypsum chytrium can parasitize inside diatom cells and cause its death, while zooplankton, such as ciliates, inhibits its excessive growth by preying on dominant algae species (Rasconi et al., 2014). Together, these biological actions determine the duration and termination of algae blooms, and affect the flow and transformation of matter and energy in the water.

7 The Ecological Significance of Interaction

7.1 Mechanisms of the formation, maintenance and decay of water blooms

The interaction between microalgae and microorganisms plays an important role in the occurrence and succession of algae blooms. The formation of water blooms is often inseparable from the help of microorganisms: heterotrophic bacteria decompose base sludge and organic matter to release nitrogen and phosphorus, nitrogen-fixing bacteria provide a nitrogen source, and promote the large-scale reproduction of algae. Once a water blossom is formed, its maintenance process is also affected by the combined influence of symbiotic and antagonistic forces (Cui et al., 2020). The symbiotic bacteria can prolong the peak of algae by continuously supplying vitamins and removing metabolic waste, while the amplification of antagonistic microorganisms (such as algaeicidal bacteria, algaephage viruses, etc.) gradually weakens the competitiveness of the dominant species of water blooms. Finally, when the enemy's effect gained the upper hand, the water flower population quickly declined and disintegrated, and a large amount of organic matter released by the algae were decomposed and utilized by bacteria, entering the next cycle (Yu et al., 2023).

7.2 Maintaining community diversity and ecological balance

The interaction between microalgae and microorganisms is also one of the key factors in maintaining water community diversity and ecosystem stability. Reciprocal symbiosis increases the complexity of the ecosystem, providing more species with living space and resource utilization pathways, thereby enhancing community diversity. For example, the algal microenvironment, as a "hot spot", promotes the coexistence of multiple bacteria and avoids the monopoly of single algae species on nutritional resources. On the contrary, various antagonisms prevent the excessive prosperity of certain species and help maintain the dynamic balance of community structure. Viruses and predators selectively eliminate dominant algae species, giving the originally disadvantaged algae and bacteria a chance to rise, thereby improving the uniformity and steady state of the system. Therefore, the positive and negative interactions between microalgae and environmental microorganisms jointly shape the structure and function of aquatic communities and maintain a healthy balance of the ecosystem (Ashraf et al., 2022; Nizamani et al., 2024).

7.3 The role of global carbon, nitrogen and phosphorus cycles

The interaction between microalgae and microorganisms plays an irreplaceable role in the Earth's material cycle. Microalgae in the ocean and freshwater fix massive CO_2 through photosynthesis every year, and a considerable portion of them are decomposed by microorganisms and return to the atmosphere or water body. In this process, elements such as carbon, nitrogen, and phosphorus are continuously transformed between algae and microorganisms, realizing the close coupling between producers and decomposed people (Krohn-Molt et al., 2017). Symboyant nitrogen fixation injects new nitrogen into a nitrogen-poor environment, improving primary productivity; the mineralization and release of organophosphorus by microorganisms provides algae with phosphorus source supplies. It can be said that without the participation of microorganisms, the fixed carbon and required nutrients of algae will be difficult to circulate in the ecosystem. Similarly, without the photosynthesis of algae, aquatic microbial communities cannot prosper (Soong et al., 2019). Microalgae-microbial interaction ensures the formation and regeneration of carbon sinks, nitrogen sinks and phosphorus sinks, and has far-reaching impacts on global climate regulation and nutrient circulation balance.

8 Summary Comments

The complex symbiotic and hostile interaction between microalgae and environmental microorganisms shapes the structure and function of aquatic ecosystems. On the one hand, symbiotic and mutual benefit promotes material circulation and energy conversion, allowing microalgae to grow efficiently, and show application potential in areas such as energy production and environmental governance; on the other hand, competition and antagonism naturally regulate algae populations, preventing excessive reproduction of a single species and causing ecological imbalance. It can be seen from typical cases that nutritional complementary symbiosis helps to improve the biomass yield of microalgae and pollution control efficiency, while the effects of hostile factors such as viruses and antagonists often end water blooms and trigger community succession. These studies have deepened our understanding of aquatic ecological processes and provided a scientific basis for the development of new technologies of algae synergistically.

Looking ahead, there are still many scientific issues in this field that are worth in-depth exploration. For example, the analysis of the specific mechanisms of algae signaling and gene interaction from the molecular level still needs to be made through multiomics and synthetic biology; the dynamic changes of the microbial community in the algae under different environmental conditions and the stability principle of multispecies symbiotic networks are also hot topics for future research.

In addition, in terms of application, laboratory results should be transformed into actual scenarios, such as building an efficient and stable artificial algae symbiosis system for wastewater resource treatment, carbon sink sequestration and biomass synthesis. Especially in the context of climate change and eutrophication of water bodies, it is particularly urgent to clarify the interaction laws between microalgae and microorganisms, which will provide a more solid scientific foundation for future biotechnology innovation and ecological environment management. We believe that with the deepening of research, the mysteries of symbiosis between microalgae and microorganisms will be revealed more comprehensively, and their ecological and application value will be more fully utilized.

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Conflict of Interest Disclosure
The authors confirm that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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