

# 海洋有害赤潮的生物防治对策

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**摘 要** 该文综述了海洋有害赤潮治理的生物方法。细菌、寄生虫和病毒等微型生物是天然水体中具有调节藻类种群动态平衡的重要潜在因子, 它们的繁殖速度非常快, 并具有宿主的专一性, 是一种非常有潜质的赤潮调控因子。根据生态系统中的食物链关系, 通过引入赤潮生物的天敌来防治赤潮也是一种治理方法。浮游动物和一些滤食性的贝类在水中与赤潮生物共存, 并能以这些赤潮生物为食, 是具有明显赤潮治理功效的生物控制剂。另一方面, 利用大型海藻与微藻间的相生相克和营养竞争等作用在养殖区域内进行赤潮的防控被认为具有较强的理论和实践意义。该文详细介绍了上述方法的原理、可行性以及局限性, 并就今后的研究方向进行了展望。

**关键词** 有害赤潮 生物对策 防治 海洋

## BIOLOGICAL STRATEGIES IN CONTROLLING OR MITIGATING MARINE HARMFUL ALGAL BLOOMS (HABS)

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**Abstract** This paper provides a review of some biological control or mitigation strategies for HABS, a problem worldwide in coastal waters. Bacteria, viruses and parasites are abundant in marine ecosystems and their abilities for rapid replication and host-specificity make them attractive HAB controlling agents; however, potential ecological impacts need to be taken into account. Species interactions between bloom microalgae and other algae play essential roles in affecting the phytoplankton sequence either by competing for the available nutrient supply or by secreting extracellular organic substances (allelopathy) into the environmental medium. This control strategy is not well understood due to a lack of experimental data, especially under natural conditions. Grazing of phytoplankton by zooplankton and suspension-feeding benthos is also considered a promising control agent, but this approach has many logistical problems and is a long way from the application stage. Collectively, some of the biological strategies discussed are decades from possible implementation, but others are further developed and thus worth considering in the immediate future.

**Key words** Harmful algal bloom (HAB), Biological strategies, Mitigation, Marine ecosystems

Globally, the problem of harmful algal blooms (HABS) has expanded considerably over the last several decades and nearly every coastal country is now affected, often by multiple toxic or harmful algal species that threaten the marine sustainability. HABS not only cause serious destruction to marine ecosystem, but also lead to massive mortality of the wild and farmed fisheries (Anderson, 1997). The task of managing HABS caused by these diverse resources is a challenging one, made all the more difficult by the diversity of the potential impacts (Anderson, 2001). Various mitigating methods have been proposed on controlling or mitigating HABS. Chemical methods, such as surfactants (Kutt & Martin, 1974), aerial

dusting with copper sulphate (Zhao *et al.*, 2001), and flocculants (Yu *et al.*, 1994; Zhang *et al.*, 2003; Cao *et al.*, 2004), have been discussed widely and thoroughly because of their remarkable ability in agglutinating and precipitating the bloom organisms; however, their potentially ecological impact, especially on benthic organisms, is a big obstacle to implementation. Physical mitigating strategies are also involved in, either skimming the surface water or using ultrasonic and ultraviolet (UV) radiation (Sugawara *et al.*, 2003); however, the results are not desirable and their potential damage on marine ecosystem needs further identification. Several groups thus focus attention on applying biological strategies to mitigation be-

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cause of their environment-friendly feature (Jeong *et al.*, 2000). A variety of organisms available in marine ecosystem are conceivably used to control HABs.

This review highlights a number of promising biological controlling or mitigating strategies worthy of further evaluation in marine ecosystem and the detail information and examples would be given respectively.

## 1 Biological strategies

### 1.1 Bacteria

Bacteria are ubiquitous and abundant in marine environments. Natural assemblage of bacteria plays an important role in the disappearance and propagation of HABs (Suttle, 1994). Requelme and Fukami (1988) had investigated bacterial community structure before and after some HABs and found high bacterial densities of *Pseudomonas* sp. 022 developed just before the alga *Asterionella glacialis*. The subsequent study showed this bacterial strain could produce a glycoprotein that acted as a growth factor for *A. glacialis* and thus stimulated the growth of the algae, which could greatly affect the bloom proliferation. Furuki and Kobayashi (1991) reported the proliferation and decline of a *Chattonella* bloom in the Sea of Harima were fluctuating with the environmental bacteria. Certain bacteria promoted the proliferation of *Chattonella* and other strains of bacteria inhibited it. The combined effects of these bacteria controlled the situation of the bloom. Other researches proved that bacteria could produce some algicidal substances affecting HABs and these substances were species-specific. Fukami *et al.* (1997) isolated a bacterial strain from natural seawater during the decline of a red tide of *Gymnodinium mikimotoi* and found that this bacterium showed substantial algicidal effects on *G. mikimotoi*. This bacterium grew actively on the extracellular organic carbon (EOC) released from *G. mikimotoi* and reached cell density to  $10^6$  cells  $\cdot$  ml<sup>-1</sup> enough to kill *G. mikimotoi*. But this strain showed almost no influence on *Skeletonema costatum*, *Heterosigma akashiwo* and *Chattonella antiqua*. Another intriguing example was the *G. mikimotoi*-killing bacterium described by Ishida (Anderson *et al.*, 2001). He had isolated a bacterial strain at the end of a bloom and found it exhibited strong and very specific algicidal activity against *G. mikimotoi*. Cells of *G. mikimotoi* could be destroyed within 24–38 h when this bacterium was introduced into a culture. It showed almost no influence on growth of other 3 tested species of blooming phytoplankton. Further studies showed that this “killing substance” was produced in response to materials excreted from the dinoflagellate in

a highly specific manner and excretion from a variety of other species did not elicit production of this substance. In turn, the compound's algicidal activity was restricted to the specific bloom species and thus selective suppression was observed. Zheng and Tian (2002) isolated 3 strains of marine bacteria from sediment of Xiamen harbor in the south of China and found them markedly inhibited the growth of *Alexandrium tamarense* under lab conditions. What's more, their culture filtrates also strongly suppressed the growth of *A. tamarense*. Similar results were obtained by Doucette *et al.* (2003). Two bacterial strains lethal to *Gymnodinium breve* separated from Gulf of Mexico were found to release a dissolved algicidal compound(s) into the growth medium, which could strongly affect the growth of *G. breve*. Further researches demonstrated that these algicidal substances were species-specific, which meant they could selectively affect the growth of bloom organisms while had little effects on the other species.

On the contrary, Baker and Herson (1978) had reported that the frequent algal crash of the food diatom *Thalassiosira pseudonanna* was due to the algicidal effects of coexisting bacteria. On the other hand, bacterial methods need several days to kill the harmful bloom microalgae. Moreover, the problem of how to multiply the bacteria to the levels needed to kill microalgae in the field ( $10^6$  cells  $\cdot$  ml<sup>-1</sup>) remained to be solved. Therefore, how to find the appropriate bacterial stains and proper utilizing way that could inhibit or kill the bloom organisms alternatively and effectively would be the focal point for further research.

More and more microbiologists are looking for practical ways to use the algicidal bacteria as a “microbial pesticides”; however, more efforts should be directed at resolving several critical issues: 1) identifying the algicide(s) in the bacteria; 2) giving thorough research on the mechanisms to regulate the algicide(s) production; 3) ensuring the ability to discriminate between target algal species; 4) and proposing a conceptual model for interactions between algicidal bacteria and their target species to serve as a testable framework for ensuing field studies.

### 1.2 Parasitism

Parasite has a dramatic effect on population dynamics of phytoplankton and its highly virulent nature has made it potential as effective control agent for HABs (Kim *et al.*, 1998). A dinospore of parasite could first attach to the host cell wall, penetrate it, and begin to multiply inside the host cell. When the cell finally bursts, it releases hundreds of new dinospores, which then move on to

infect other hosts.

There are a variety of different parasite species which can infect marine organisms, and a number of these are dinoflagellates. *Amoebophrya ceratii*, for example, was a well-known intracellular parasite of free-living dinoflagellates and could infect many microalgal populations, including the toxic dinoflagellates of *Gymnodinium sanguineum*, *Gyrodinium uncatenum* and *Scrippsiella trochoidea* (Coats & Adam, 1996). Erard-Le *et al.* (2000) first reported the effect of parasitism on the toxic dinoflagellate *Alexandrium minutum*. He elucidated that cells of *A. minutum* collected from Penzè River in France in 1997 were infected by the sporocysts of an unknown parasite. Moreover, this parasite was found to infect several other dinoflagellate species simultaneously in the laboratory. The parasite-induced mortality indicated that this parasite was capable of removing a significant fraction of dinoflagellate biomass in a short time, raising the possibility of its use as a biological control agent of toxic dinoflagellate blooms.

A key issue with respect to parasite control is that of host specificity, as it would be ideal if an introduced parasite would only attack the target HABs organisms and then die-off after the demise of the bloom. Resolution of these specificity issues is clearly important, although an argument could be made that absolute host specificity should not be a requirement because the standard were seldom imposed in control of terrestrial pests (Anderson *et al.*, 2001).

However, the use of parasitism as the biological control agents to regulate HABs has never been openly discussed or debated and is limited by lack of knowledge of several key questions. For example, we don't know its potential impacts on marine ecosystem and the unpredictable effects of interfering with species diversity. The precise classification of this organism has not been elucidated yet. Parasite would be a long-term area of investigation with respect to the control of HABs population.

### 1.3 Viruses

Viruses are very abundant in coastal seawater and essential to the dynamics of marine ecosystems (Suttle, 1994). Some of them could infect algae and thus be implicated in the demise of the bloom. Viruses can attack bloom organisms in the same way that parasites do, therefore, they have the potential to be highly specific and effective in controlling bloom. Bratbak *et al.* (1993) reported the collapse of a Coccolithophorid *Emiliania huxleyi* bloom occurred simultaneously with the appearance of many viruses in the surrounding water and inside the algal

cells. Nagasaki *et al.* (1994) identified there was a potential linkage between the collapse of a *Heterosigma* bloom and the appearance of virus particles within the algal cells. Keizo *et al.* (1999) had reported only growth of *H. akashiwo* was inhibited when *H. akashiwo* virus crone 01 (HaV01) was inoculated into a mixed algal culture containing *H. akashiwo*, *C. antiqua*, *Heterocapsa triquetra*, and *Ditylum brightwellii*. Inoculation of HaV01 and *H. akashiwo* H93616 into a natural seawater sample had the similar results. However, a natural *H. akashiwo* HAB sample did not exhibit any conspicuous sensitivity to HaV01. Such results were presumable because of the great diversity of the host species with respect to virus infection.

However, the knowledge of viruses that infect marine phytoplankton is limited. On a theoretical level, the rapid replication and host-specific features make viruses attractive as biological control agents (Suttle, 1996). This means virus could potentially target a specific algal species and affect it rapidly, leaving closely related organisms unaffected. In reality, viruses are sometimes so host-specific that they are unable to infect different genetic strains of the same host species. Therefore, it would be necessary to isolate a suite of viruses which obtain a broad spectrum of infectivity. However, whether such viruses exist is a legitimate question, and whether they would be used effectively in control remains unknown.

### 1.4 Other algae

Macroalga plays an important role in affecting marine phytoplankton sequence, either by secreting extracellular organic substances (allelopathy) into the environmental medium or by competing for the available nutrient supply, and is suggested to be potential HABs controlling agent (Gross, 1999; Nakai *et al.*, 1999).

Allelopathy is the direct or indirect effect of a plant on another plant through the release of compounds into the environment to affect other organisms (Rice, 1984). Inderjit & Dakshini (1994) first gave a view of allelopathic activities in aquatic habitats with particular emphasis in algae. They pointed that the chemical produced from algae could influence not only other algae in their close vicinity and their own growth potential (autotoxicity), but also the associated microorganisms (e. g. epiphyte) and nearby higher plants and animals. Satoshi *et al.* (1999) evaluated the inhibitory effects of different species of macrophytes (*Egeria densa*, *Cabomba caroliniana*, *Myriophyllum spicatum*, *Ceratophyllum demersum*, *Eleocharis acicularis*, *Potamogeton oxyphyllus*, *Potamogeton crispus*, *Limnophila sessiliflora*, or *Vallisneria*

*denseserrulata*) on growth of blue-green algae (*Microcystis aeruginosa*, or *Phormidium tenue*) in coexistence culture. Results showed that only *C. caroliniana* or *M. spicatum* inhibited the growth of the tested microalgae, with the inhibitory effects of *M. spicatum* being stronger than those of *C. caroliniana*. They suggested that macrophytes might inhibit microalgal growth by allelopathy and the inhibitory effects were species-specific. Qiu and Dong (2003) had proved that *Ulva pertusa* (a green macroalga) had obviously negative effects on *H. akashiwo* and *A. tamarense*, the toxic bloom microalgae, through allelopathic pathway. Not only their fresh tissue, but also the dry powder and culture medium filtrate strongly affected the microalgal growth. Similar results were obtained in out laboratory. *Ulva pertusa* and *Gracillaria lemaneiformis*, the commercial macroalgae distributed widely in coastal China, were observed to have negative effects on the growth of 4 species of toxic dinoflagellates (*Propocentrum donghaiense*, *Amphidinium carterae*, *Alexandrium tamarense* and *Scrippsiella trochoidea*). Further identification demonstrated that the allelopathy between macroalgae and microalgae might be the most possible reason<sup>1)</sup>.

What's more, the anti-algal bioactive compounds extracted from macrophytes were also proved to be algicidal. Kakizawa *et al.* (1988) reported that 6Z-, 9Z-, 12Z-, 15Z- octadecatetraenoic acid (ODTA) extracted from the brown alga *Cladosiphon okamuranum* had an immediate lethal effect on some microalgae. Lectin prepared from *Gracillaria verrucosa* had negative activities against the growth of *C. antique* bloom. Addition of the seaweed lectin at 50  $\mu\text{g}\cdot\text{ml}^{-1}$  could alter the cellular morphology, which became shrunken form, and its growth was completely suppressed (Hiroyuki *et al.*, 1993). Koki *et al.* (2003) investigated the algicidal effect of phlorotannins extracted from the brown alga *Ecklonia kruome* on 3 species of red tide microalgae (*Karenia mikimotoi*, *Cochlodinium polydrikoides* and *C. antiqua*). When the microalgae were exposed to a medium containing 150  $\text{mg}\cdot\text{L}^{-1}$  crude phlorotannins, the swimming cell density of *K. mikimotoi* and *C. polydrujiudes* decreased to less than 2% of the initial density within 30 min. The cells became round, expanded and then burst. No change was observed on *C. antiqua* in the 500  $\text{mg}\cdot\text{L}^{-1}$  medium within 3 h after inoculation. However, over 99% of the cells were even destroyed in 100  $\text{mg}\cdot\text{L}^{-1}$  medium after 24 h. All the results above described provide the feasibility

of utilizing macrophyte as promising candidates for restraining the action of HABs.

Nutrition competition is another factor affecting HABs development. Marshall and Orr (1949) had reported that microalgae only bloomed when macroalgae were not present. In the San Francisco Bay-Estrarine mesocosms, resource competition for inorganic nitrogen was identified as the probable cause of the depression of microalgae by *Ulva* (Smith & Home, 1988). In the Venice lagoon in algal growth season, microalgae grew only after seaweed decay, after seaweed reaping, or in the most polluted area (Sfriso *et al.*, 1989). Results described above suggested that macroalgae could out-compete the toxic bloom microalgae for available nutrients, reducing the size of bloom organism population through competitive exclusion.

However, the potential for this strategy to be successful is exceedingly difficult to evaluate due to the lack of experimental data, because the macroalgal species involved is not clear. Present research only provide evidences that some nearshore, benthic species have potentially inhibitive effects on HABs development; however, most HABs thrive in offshore waters, where the introduced macroalgae could not exist. Another missing detail is the manner in which the two species interact with each other in culture, not just in small flasks, but in larger outdoor containers under the natural condition. Therefore, more and more researches would focus on: 1) screening out macroalgal species that could be utilized in offshore waters; 2) determining a quantitative relationship to reveal a macrophyte capable of controlling algal growth under natural conditions and 3) demonstrating the distinct allelopathic effect that such a macrophyte makes.

### 1.5 Grazing by zooplankton and suspension-feeding bivalves

Zooplankton, small animals that co-occur with algae and graze them as food, is conceivably considered as a biological control agent to control HABs. It grazes different phytoplankton cells at different rates and has different impacts on phytoplankton community development. There are three types of grazing strategies for zooplankton. First, the grazing rate gets increasingly higher as phytoplankton concentration approaches zero and its grazing will have limited effects on controlling red tide occurrences. Secondly, the grazing rate isn't at its maximum until the phytoplankton concentration is very high. Such grazing

1) Wang Y (王悠), Yu ZM (俞志明), Song XX (宋秀贤), Zhang SD (张善东). Effects of macroalgae on growth of 2 species of bloom microalgae and the interactions between the microalgae in laboratory culture. *Environmental Science* (环境科学). (accepted)

would contribute to preventing the occurrence of HABs to some extent. Thirdly, the grazing rate will not increase with the increasing phytoplankton concentration until an optimum grazing rate is reached and then decrease with the increasing phytoplankton concentration. Such grazing will most efficiently control HABs (Sun *et al.*, 2004).

Martin *et al.* (1973) suggested that marine ciliates could be cultured and used for control of *G. breve* cells. Likewise, Shirota (1989) considered the use of zooplankton, such as *Acartia clausi*, in controlling HABs. However, both authors arrived at the estimation that was completely unrealistic with respect to the cost, space, and facilities. For example, Shirota (1989) calculated that a 33 000 m<sup>3</sup> would be needed to hold sufficient zooplankton to treat a red tide 100 m long and only 1 m deep. Furthermore, this tank would have to be maintained constantly during the red tide season so that zooplankton would be ready for deployment at the appropriate time. This is not an idea worth of pursuing. In our country, we have some fundamental data on zooplankton grazing on microalga (Sun *et al.*, 2003a, 2003b); however, little is known about their effects on development of HABs (Sun *et al.*, 2004).

Grazing by suspension-feeding bivalves is known to play an important role in controlling phytoplankton biomass in shallow, enclosed estuaries and could therefore potentially provide an effective control mechanism in shallow waters (Alpine & Cloern, 1992). Japanese researchers took the predator concept one step further to examine the possibility using bivalves, such as clams or oysters, as a massive filter to clear the water of toxic algae (Shirota, 1989). Satoshi and Yasushi (1994) had conducted some experiments to determine whether red tide water masses could be controlled by the filter-feeding bivalve, *Mytilus edulis galloprovincialis*, cultured on rope collectors. The mussels effectively retained food particles larger than about 4  $\mu\text{m}$ , and their retention rate increased with the increase of in plankton density between  $10^5$  and  $5 \times 10^6$  cells  $\cdot \text{ml}^{-1}$ , which was equal to the density of plankton in red tide water masses. Thus, plankton in red tide water masses should be removed rapidly from seawater by mussels through their retention and excretion, since the faeces excreted by mussels that had been fed on plankton were deposited speedily. Furthermore, the faeces excreted by mussels that contain a large amount of organic matter unabsorbed by the mussels, were eaten by an edible deposit-feeding sea cucumber, *Stichopus japoni-*

*cus*. Thus, certain species of plankton concentrating in red tide water masses may serve not only as food sources for filter feeders and deposit feeders, but can also be removed from the seawater. Bivalves at historical peak abundance levels in Great South Bay, New York, could have the potential to control the initiation of brown tides at low density ( $\leq 20\ 000$  cells  $\cdot \text{ml}^{-1}$ ) of *Aureococcus anophagefferens*, which were below the cell density threshold that inhibited calm filtration rates<sup>1)</sup> (Bricelj *et al.*, 2000). However, bivalves vary in their ability to filter water and some could filter 10 – 50 L  $\cdot \text{h}^{-1}$ . Here again, the calculations reached impractical levels, as a barrier of cages containing oysters would need to contain 720 000 individuals just to treat a volume of water passing through a square 50 m on a side (Shirota, 1989). Polyculture of bivalves in shallow shrimp ponds may also allow control of algal blooms, which can cause anoxic events and shrimp mortalities in areas of extensive shrimp culture, such as the Bohai region in China (Anderson *et al.*, 2001). Further studies are required to test the feasibility of this biological control mechanism in shallow ecosystems.

## 2 Conclusion

In general, biological methods have effective, species-specific and environment-friendly features, which make them more outstanding than other chemical and physical methods in HABs mitigating and controlling. However, further considerations are needed to identify the logistic and feasibility in reality. More researches will focus on conforming different methods into utilization. For example, flocculation is much effective in scavenging the diatom while shows no obvious effects on the dinoflagellate, while bacteria and virus could inhibit the dinoflagellate growth remarkably. Using the flocculation and microbial agents together might have superior effects on removing the mixed-species bloom. Zhou *et al.* (2004) suggested using hydroxyl radical in eliminating *Gymnodinium mukimotoi*, a toxic bloom microalga, and found it effective and environmental-friendly. Liang *et al.* (2001) combined biological and chemical methods together and suggested a method using biomass carrier as algicide to control HABs. Then again, how to manipulate different agents to proper proportions to make it more effective in controlling and mitigating the blooms but have no disadvantages to the ecosystem would be the key point.

1) Schaffner RA (1999). *The Role of Suspension Feeding Bivalves in the Initiation and Control of Aureococcus anophagefferens Blooms*. MS. dissertation of State University of New York, Stony Brook, 82.

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