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Review

Principles and research progress of physical prevention and control technologies for algae in eutrophic water

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SUMMARY

The abnormal reproduction of algae in water worldwide is prominent in the context of human interference and global climate change. This study first thoroughly analyzed the effects of physical factors, such as light, temperature, hydrodynamics, and operational strategies, on algal growth and their mechanisms. Physical control techniques are safe and have great potential for preventing abnormal algal blooms in the absence of chemical reagents. The focus was on the principles and possible engineering applications of physical shading, ultrasound, micro-current, and ultraviolet (UV) technologies, in controlling abnormal algal reproduction. Physical shading can inhibit or weaken photosynthesis in algae, thereby inhibiting their growth. Ultrasound mainly affects the physiological and biochemical activities of cells by destroying the cell walls, air cells, and active enzymes. Micro-currents destroy the algal cell structure through direct and indirect oxidation, leading to algal cell death. UV irradiation can damage DNA, causing organisms to be unable to reproduce or algal cells to die directly. This article comprehensively summarizes and analyzes the advantages of physical prevention and control technologies for the abnormal reproduction of algae, providing a scientific basis for future research. In the future, attempts will be made toward appropriately and comprehensively utilizing various physical technologies to control algal blooms. The establishment of an intelligent, comprehensive physical prevention and control system to achieve environmentally friendly, economical, and effective physical prevention and control of algae, such as the South-to-North Water Diversion Project in China, is of great importance for specific waters.

INTRODUCTION

As the global economy advances, urban industrial activities and living conditions improve, which exasperate water eutrophication and algal pollution. Algal blooms occur in the nutrient-rich surface waters of tropical and subtropical regions.[1,2] Algae include the prokaryotic, protist, and plant kingdoms.[3] Some contain nuclei, membrane vesicles, and organelles, which are characteristic of eukaryotes, and require oxygen for survival. In recent decades, human activities have created ideal conditions (i.e., elevated levels of nitrogen and phosphorus in water) for algal blooms. *Chlorella*, *Diatom,* and *Cyanobacteria* easily cause algal blooms.[4] Harmful algal blooms (HABs) caused by eutrophication occur frequently in coastal oceans.[5] HABs in oceans, often referred to as red tides, considerably threaten marine ecosystems.[6] Moreover, HABs in freshwater bodies (lakes, reservoirs, ponds, rivers, and artificial canals) are pressing environmental problem.[7]

Abnormal algal blooms affect the appearance of water, to the clogging of water plant equipment, and complicate treatment processes.[8] Meanwhile, algae in water can adversely affect drinking water quality and water treatment processes, interfering with the physical and chemical purification processes of water.[9] Although coagulation and sedimentation can remove more than 90% of algae in influent water, they may lead to the clogging of filter membranes, which threatens the safety of urban drinking water.[10] In addition, algae can release harmful substances such as cyanotoxins, which can affect the survival of fish and shellfish, negatively impact aquaculture, and threaten human health through the food chain.[11,12] Sub-lethal amounts of cyanotoxins in drinking water are considered as risk factors for the development of primary liver cancer.[13] It is important to pay attention to the problem of algal blooms, both in the management of water quality in lakes and reservoirs and particularly in the treatment of drinking water. Thus, the mechanisms of nutrient regulation and algal outbursts in water, along with their

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prevention and control, have emerged as critical areas of water environment research and are critical issues currently being addressed worldwide.

The methods reported or used in the literature, patents, and engineering practices involve physical, chemical, and biological approaches. These methods include filtration, coagulation, clarification, flotation, algaecide, ozone treatments, and photolysis.[14] Some algal control technologies, such as chemical dosing, can be costly and may negatively affect ecosystems and human health.[15] In addition, the overuse of certain algal inhibitors may result in their accumulation in water, potentially harming aquatic organisms and ecosystems.[16] Biological algal control methods are relatively costly, especially when applied on a large scale, and are prone to biological invasion.[17] Therefore, finding an environmentally friendly and safe method for inhibiting abnormal algal proliferation, particularly for drinking water sources, is a research hotspot in aquatic ecological restoration. Physical control has a relatively low economic cost and ecological impact. Many studies worldwide have explored the causes of abnormal algal proliferation in lakes, rivers, reservoirs, and other physical factors.[18] However, comprehensive summaries or reviews of the principles, effects, and engineering applications of physical prevention and control technologies are lacking, making it difficult to support the improvement of these technologies. Scientometric analysis can identify critical research in a target field and current and potential research hotspots and trends.[19] Through a study of published articles and patents, their graphical relationships can intuitively and clearly describe the knowledge structure and evolutionary history in a specific environment.

This article analyzes and summarizes the effects of physical factors on algal bloom growth. The relevant literature and patents retrieved were visualized, and mechanisms, effects, and possible engineering practices of typical physical control techniques for algal growth were reviewed. This study aimed to achieve the following objectives: (1) explore the effects of physical factors (light, temperature, hydrodynamics, and operational strategies) on algal growth and summarize their mechanisms; (2) analyze and summarize the mechanisms, effects, and engineering practices of typical physical control technologies (physical shading, ultrasonic, micro-current, and ultraviolet (UV) technologies on algal growth control; and (3) determine adequate directions and provide feasible suggestions for future research as well as engineering applications of algal physical prevention and control. This article aims to bridge these gaps by offering a comprehensive evaluation of physical prevention technologies and a foundation for their advancement.

METHODOLOGY AND ANALYSIS

Web of Science (WoS) is renowned for its high-quality documentation, making it a preferred resource for scientometric research.[20] For this review, a comprehensive literature search was conducted within WoS using “Topic Search” criteria, specifically “Physical prevention technologies for algae” and “Physical control technologies for algae.” A manual review of all articles was undertaken to enhance the precision of the analyses. To conduct a literature hotspot analysis, the curated dataset was input into CiteSpace 6.1. Patent searches and hotspot analyses were performed using the incoPat website.

Typical physical prevention and control technologies with promising futures were selected for review by analyzing research hotspots in the literature and patents. Their effectiveness was evaluated by exploring the mechanisms, effects, and application. A table was compiled for the comprehensive comparison and analysis of various algal prevention and control technologies. The figures in this article were produced using CiteSpace 6.1, incoPat, and Adobe Illustrator 2022.

EFFECTS OF PHYSICAL FACTORS ON ALGAL GROWTH AND BLOOMS

Environmental conditions considerably affect the phytoplankton growth and community structure of phytoplankton.[21] The physical factors related to algal growth include light, transparency, water temperature, air temperature, flow speed, and wind speed. Among them, light and water temperature are directly related to algal growth, whereas transparency, temperature, flow speed, and wind speed are all indirectly related to algal growth.[22] Key factors influencing the occurrence of algal blooms are shown in Figure 1. The effects of physical characteristics, such as light, temperature, hydrodynamics, and operational strategies, on algal growth were analyzed. The factors affecting algal bloom formation were then further summarized to provide a scientific basis for exploring physical prevention and control technologies.

Effect of light on algal growth and blooms

Light is the energy source for photosynthesis, which is the basis for the growth and metabolism of autotrophic organisms. It affects the carbon fixation rate as well as the respiration intensity and energy charge level of algae.[23] Changes in lighting conditions will affect the buoyancy and molecular synthesis of algae.[24] Light affects algal growth mainly through its intensity. The photoperiod, light wavelength, light transmittance of the water, and diving depth of algae can affect algal growth.

The growth rate of algae increases as the light intensity increases from zero to an appropriate light intensity. After the light intensity increases to the saturation point (after the light level increases to a certain value, the photosynthetic rate does not continue to increase), the photosynthetic rate decreases or even stops, and photoinhibition occurs.[25] Intense light decreases the rates of electron transfer and quantum production in algal cells. It also causes the rate of damage to algal cell photoreaction center proteins to exceed the rate of light repair, considerably reducing photosynthetic activity.[26] Additionally, the optimal light intensity range of different algae is diverse, depending on the other pigment–protein complexes used to capture light energy in the photosynthetic organs of algae.[27] This also affects the aggregation patterns of different algae.[28] The correlation between a light intensity of 1000 lx–5000 lx and an increase in the algal population at each temperature can be expressed using semi-logarithmic or exponential equations. It is generally recognized that the range of 3000 lx–4000 lx is the optimal light intensity for algae. The relationship between light and the algal growth rate can be expressed using Equation 1 (WASP6 Manual).

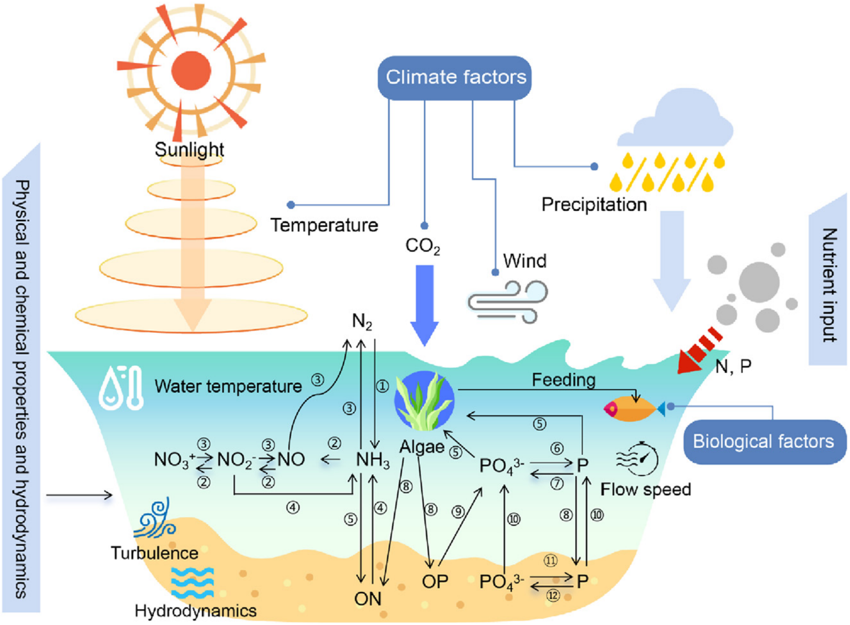

Figure 1. Generalization diagram of factors influencing the occurrence of algal blooms (of which, ① nitrogen fixation, ② nitrification, ③ denitrification, ④ ammonification, ⑤ assimilation, ⑥ adsorption, ⑦ desorption, ⑧ sedimentation, ⑨ mineralization, ⑩ re-suspension, ⑪ adsorption complexation, ⑫ dissolution)

$$X_L = \frac{e}{K_e D}\left[exp\left\{-\frac{I_0}{I_S}exp(-K_e D)\right\} - exp\left\{-\frac{I_0}{I_S}\right\}\right] \quad \text{(Equation 1)}$$

Where, X_L—light impact factor, unitless; D—water depth, m; K_e—extinction coefficient, m^{-1}; I_0—radiant intensity at the water surface (assuming 10% reflection), kcal m^{-2} d^{-1}, usually 0.9; I_S—algae light saturation constant, kcal m^{-2} d^{-1}.

$$K_e = 0.0088P_{Chla} + 0.054P_{Chla}^{0.67} \quad \text{(Equation 2)}$$

Where, P_{Chla}—algae chlorophyll *a* content, μg/L.

The length of a photoperiod directly affects algal growth. A photoperiod is the proportion of light time and dark time allocated over a 24 h period, also known as the light/dark ratio. Algae exhibit different photoperiods. For example, *Cyanobacteria* require short photoperiods, whereas *Chlorella* prefer long photoperiods.[29] Chlorophyll, carotenoids, and phycobilins are the main photosynthetic pigments found in algae. These pigments have different absorption bands for light, which lead to the different absorption and utilization of light at different wavelengths by algae owing to differences in pigment composition. Transmittance is the degree to which light can penetrate water. The higher the transmittance, the deeper light can penetrate the water and the more efficiently algae will photosynthesize. Algal growth can be hindered by prolonged exposure to water with a low light transmission.[30] Algae are generally more abundant in shallow water because of the greater light intensity used for photosynthesis in shallow water.

Effect of temperature on algal growth and blooms

Temperature is a critical environmental factor affecting algal growth. It affects the utilization efficiency of water nutrients by algae as well as the physiological activity of algal cells. Generally, the higher the temperature, the faster algae grow, and the growth rate of algae can be controlled by adjusting the temperature of water. Water temperature directly affects algal growth by influencing enzymatic activities. It mainly affects growth and proliferation by influencing the photosynthesis, respiration, and metabolic functions of algae. Meanwhile, changes in water temperature alter the solubility or decomposition rate of various nutrients in water, influencing the efficiency, degree of absorption, and utilization of nutrients by algae. Suitable temperatures facilitate photosynthesis, accelerate enzymatic reactions, increase biomass, and promote the spread of large algae and blooms. It was reported that the average annual algal biomass will increase by 0.145 times if the average annual temperature increases by 1°C.[31] Goldman, Carpenter,[32] and Eppley[33] obtained empirical Equation 3 to represent the relationship between the algal proliferation rate and temperature based on an investigation of various algal species *in situ* involving numerous experiments.

$$\mu = 0.590 \times (1.066)^T \quad \text{(Equation 3)}$$

Where, μ—algal proliferation rate, 1/d; T—temperature, °C.

The extent of adaptation to temperature in algal species determines the seasonal succession of algal communities.[34] The dominant algal species in aquatic environments vary significantly among different seasons. For example, *Cyanobacteria* and *Chlorella* are dominant in summer, whereas *Diatom* dominate in winter. *Diatom,* with their unique structure, can adapt a wider range of water temperature, and they have a higher tolerance to low water temperatures, surviving in the range of approximately 10°C–40°C, with the optimum temperature being between 20°C and 30°C. The optimum temperature for *Cyanobacteria* is relatively high; thus, they are often in summer. Indoor simulation tests showed that the growth rate of *Microcystis aeruginosa* increased exponentially with an increase in water temperature at 30°C–35°C. However, after the growth reached its maximum, the growth rate decreased sharply, *M. aeruginosa* began to precipitate, and the green color faded away.[35]

In addition, water temperature can change the species and community structure of algae in the water, thereby affecting the ecosystem in the water.[27] If the water temperature is too high, algal species may become unitary. If the water temperature is too low, the growth and reproduction of algae are limited. Thus, changes in the water temperature can affect the balance of aquatic ecosystems. The higher the eutrophication of water is, the greater the effect of temperature on algal growth.[36] When nutrient levels in the water are too high, algal blooms occur and the temperature affects more algae. However, rapid changes in water temperature during an algal bloom can lead to a sudden decrease in algal populations or even the disappearance of the bloom.[37] This is more likely to occur in shallow waters, where water temperatures can change rapidly and directly.

Effects of hydrodynamics on algal growth and blooms

Hydrodynamic conditions significantly affect algal growth in rivers, lakes, and reservoirs.[38,39] The effects of hydrodynamic conditions on algae and the corresponding prevention and control strategies have become a hot topic internationally.[40] Dam construction has altered the hydrodynamic conditions of natural rivers, causing significant changes in the basic hydrological characteristics of aquatic ecosystems and the geochemical cycling of nutrients. For example, some artificial reservoirs cause thermal stratification by increasing the water depth and reducing flow velocity, which promotes nutrient retention and leads to abnormal algal growth.[41–43]

Hydrodynamics can regulate the cohesive properties of algal cell populations and can act directly on algal cells to produce scouring effects on algae, ultimately affecting the growth and community structure of algae.[44,45] Hydrodynamic conditions can suspend sediments in water and alter the distribution of nutrients, such as nitrogen and phosphorus, in aquatic environments, providing more dissolved bioavailable nutrients for algal growth.[46] Wind speed directly affects algal growth.[47] Changes in turbulence due to wind speed alter the scale of nutrient diffusion in water, thereby affecting the uptake and utilization of nutrients by algal cells. This has been verified by comparing the movement speed of phytoplankton with the turbulent fluctuation speed (Equation 4).[48]

$$\varnothing = \mathrm{V_S}/15\mathrm{V_K} \tag{Equation 4}$$

Where, $\mathrm{V_S}$ is the movement speed of phytoplankton, and $\mathrm{V_K}$ is the turbulent fluctuation speed, when $\varnothing < 1$, it means there is effective entrainment.

In addition to the effects of these common environmental factors, operational strategies can indirectly affect algal growth by decreasing residence time and disrupting stratification.[49] Previous studies have reported that maintaining low water levels during bloom-prone periods can help control algal blooms.[43] To date, the time scales for applying operational strategies to mitigate algal blooms have been primarily long-term.[38] The residence time of water bodies has a pronounced effect on algal blooms. For example, the Three Gorges Reservoir in China suppresses algal blooms by increasing flow rates.[50] Dramatic fluctuations in water levels, particularly rapid declines, may increase water exchange, weaken stratification, and inhibit algal blooms.[43]

The circulatory cycle in a water body can indirectly affect the growth and reproduction of algae. If the cycle is short, algal growth may be limited.[51] Water dynamics, such as waves and tides, can also affect algal growth.[52] They help algae spread and bring nutrients into water.[53] The critical flow rate also indirectly affects algal growth and can be used as an indicator when studying the effect of the flow rate on algal growth.[54,55] It is the flow rate at which the algal growth rate is maximized, and the critical flow rate is spatially and temporally localized. The rate of algal growth under different water temperature, light, nutrient salts, and hydrodynamic conditions can be expressed using Equations 5, 6, 7, 8, 9, and 10.[56]

$$\mu = f(T) * min[f(N), f(P)] * f(L) * f(\mu) \tag{Equation 5}$$

$$f(T) = \mu_{max} * \theta^{(T - T_{max})} \tag{Equation 6}$$

$$f(N) = \frac{TN}{TN+K_N} \tag{Equation 7}$$

$$f(P) = \frac{TP}{TP+K_P} \tag{Equation 8}$$

$$f(L) = \frac{1}{K_e D} \ln \frac{I_0+I_S}{I_0 e^{-2K_e D}+I_S} \tag{Equation 9}$$

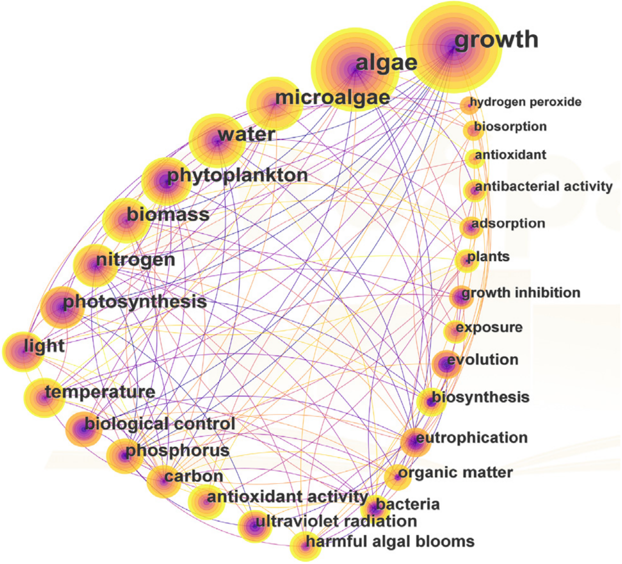

Figure 2. Keywords for bibliometric-based algal prevention and control technologies (2011–2023)

$$f(\mu) = V^{\gamma u} \tag{Equation 10}$$

Where, μ, μ_{max} is the actual and maximum algal growth rates, respectively, 1/s; T, T_{max}, θ is the actual water temperature of the water and the optimal water temperature for algae growth (°C), and the temperature correction factor; TN, K_N, TP, K_P is the total nitrogen, nitrogen half-saturation constant, total phosphorus and phosphorus half-saturation constant of water, respectively, mg/L; D is the water depth, m; K_e is the extinction coefficient, m^{-1}; I_0 is the radiant intensity at the water surface (assuming 10% reflection), kcal m^{-2} d^{-1}, usually 0.9; I_S is the algae light saturation constant, kcal m^{-2} d^{-1}; γ, V is the coefficient to be determined; u is the flow rate, m/s.

Based on the above analysis, it can be concluded that physical factors have an important influence on algal growth. Under low light or high temperatures, the photosynthetic efficiency of algae is reduced, which inhibits their growth. By controlling the speed and direction of water flow, algal aggregation can be effectively reduced, thus controlling their numbers. Therefore, physical control measures, such as physical shading, hydrodynamic regulation, and other measures that affect algal growth, should be implemented. These physical methods can inhibit the abnormal proliferation of underwater algae. The presented analyses underscore the necessity of a multifaceted approach for the development and implementation of physical control technologies.

PROGRESS IN THE RESEARCH AND APPLICATION OF ALGAL PREVENTION AND CONTROL TECHNOLOGIES

Bibliometric analysis

In recent years, extensive research has been conducted on algal prevention and control technologies, and many studies have been published. The retrieved publications were analyzed in CiteSpace for "keywords" to produce Figure 2, with an annual time slice and a top threshold of 60. The results show that the influence of physical factors, such as light and temperature, on algal growth is essential for preventing and controlling algae in water, and these factors form the basis of essential prevention and control technology. According to recent research, a large number of the reported control measures for algal control mainly involve the control of nutrients, including nitrogen and phosphorus, in water. This has been conducted to decrease the degree of water eutrophication from sources as much as possible so that algae lack the necessary nutrients to grow and bloom.[57] The literature deals with several algal control measures, and the keywords can be summarized according to their principles as physical, chemical, and biological methods.

Patent analysis

Patent analysis represents the actual invention and application of technology, and it is an essential source of information regarding the current state of research in a particular field, particularly the potential for application.[58–60] In this study, patents related to algal prevention and control technologies were searched using the incoPat patent search system. Subsequently, keyword clustering of patents related to algal prevention and control technologies was performed to generate Figure 3. The results show that, to effectively reduce algal biomass, reduce the frequency and intensity of blooms, and control the secondary disasters associated with blooms, single techniques to control blooms using physical, biological, and chemical methods have been developed. For example, several key technologies, such as integrated ecological porous substrate design and biological manipulation technologies can be used. However, similar to the results of the bibliometric analysis, patents on the physical prevention and control technologies for algal blooms are limited.

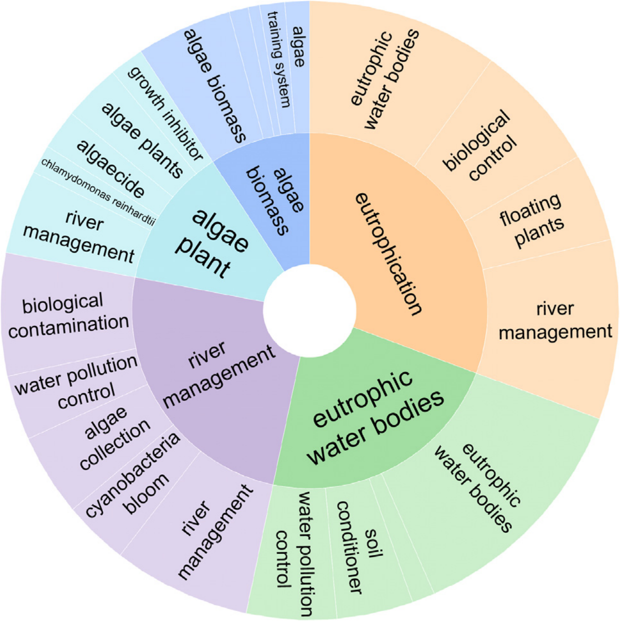

Figure 3. Clustering of algal prevention and control (2010–2022)

In terms of algal control, a cluster analysis of relevant patents by incoPat yielded Figure 4. The term "blocking rod" had the largest number, indicating that this term has been widely reported and applied in algal control. Blocking rods are generally categorized as either rigid or flexible fences. Rigid fences are generally made of steel tubes, whereas flexible fences are generally made of anti-UV nonwoven fabrics.[61] Blocking rods are mainly used to prevent, control, collect, and treat algae, and they have good practicality, prevention, and control effects. For example, algae can be effectively intercepted using a blocking rod without affecting ecological landscapes. The use of a flexible blocking rod allows for free switching without disassembly. This, in turn, allows for the free passage of boats while controlling algae. Some chemical agents play vital roles in preventing and controlling algal blooms. For example, the addition of chemical agents can effectively regulate the level of oxygen in water, inhibit algal growth, and improve water quality. The synergistic effect between the components, such as composite ecological treatment agents, simultaneously inhibits the abnormal proliferation of algae and protects the ecological environment of aquaculture water.

Comparative analysis of physical, chemical, and biological methods

Based on the above bibliometric and patent analyses, detailed summaries, comparisons, and analyses were performed for physical, chemical, and biological methods (Table 1). This article critically evaluates these technologies, emphasizing their scalability, cost-effectiveness, and environmental sustainability.

Algae can be removed directly using physical means, by reducing or even eliminating the conditions required for algal blooms or by settling the algae to the bottom of water. Globally, the development of emergency technologies for algal bloom removal involves mechanized salvage. In the 1960s and the 1970s, direct filtration for algal removal was commonly used to treat water-containing algae. Subsequently, other physical control methods, such as air flotation, have been used to remove algae via solid–liquid separation. UV radiation kills algae by affecting their DNA. Physical shading to control algae is a proven technique that directly cuts off or diminishes light sources. Physical prevention and control techniques, such as those employing ultrasound and micro-current, which have been reported in recent years, include physical methods for green algal removal.[62] Physical algal control techniques are not only important in reducing bloom outbreaks but are also effective in reducing manual treatment costs. Physical algal control technologies are relatively inexpensive to implement, and a one-time investment can be used multiple times over a longer period. In addition, the sustainability and environmental friendliness of these technologies make them economically viable for long-term use. Physical control technologies are expected to have a considerable potential for improving the intelligence and networking of control equipment in the future.

Chemical methods for algal removal involve directly adding chemicals to the water to inhibit the growth of algae, which has been widely used for algal removal. Pre-oxidation uses the strong oxidizing property of a strong oxidizing agent to produce a bactericidal effect in water to achieve the purpose of an algaecide. Algal removal agents are composite agents with broad-spectrum bactericidal ability that can effectively penetrate the cell wall, decompose DNA, and, thus, inhibit its reproduction or kill it directly. Activated carbon adsorption was found to remove nearly 99% of algae under certain conditions.[63] The modified clay method is preferred owing to its bridging net trapping properties and usually achieves algal removal efficiencies of more than 95%.[64] Although chemical control techniques can remove algae quickly and

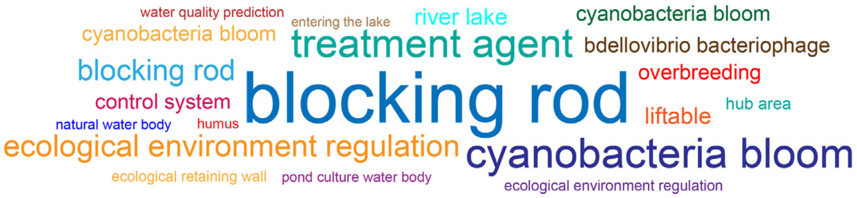

Figure 4. Algae prevention and control word cloud (2010–2022)

effectively, they often fail to address the root causes of the problem. Some chemical control techniques only eliminate surface algae, which may cause serious environmental problems such as the release of toxic substances and disruption of the ecological balance of waterbodies. Chemical control techniques are costly and require long-term investments, which is a heavy burden on some developing countries and regions.

Biological methods for algal control have been widely explored and used in practical engineering applications. They involve utilizing interspecies competition to transform harmful algae into water, thus controlling HABs and gradually restoring the health of aquatic ecosystems.[65] However, the safe introduction of organisms into water and the cost of the used technologies are key issues that need to be considered. The scalability of algal biocontrol technologies varies with environmental conditions. For example, when the environment is under high-salinity or high-alkalinity conditions, the application of algal biocontrol technologies faces more challenges. In addition, the application of algal biocontrol technologies is affected by factors such as geography and climate, and the effectiveness of control technologies may be reduced in areas where the geographic environment is more favorable for algal growth. Compared to traditional chemical treatment methods, biological control technology is less costly and more economically efficient. In addition to the effects of water treatment, using biological control technology for algal control can support the balance and stability of aquatic ecosystems, further enhancing the ecological benefits of water. In practical applications, it is also necessary to comprehensively use other governance methods to achieve the comprehensive management of algal problems.

Physical, chemical, and biological methods have been extensively investigated, developed, and applied to algal control and treatment. Chemical methods can easily result in secondary pollution and are relatively expensive. Biological methods generally have the lowest cost but require a long time, which is not conducive to the urgent treatment of algal blooms, and they have a high environmental impact. Novel physical technologies, such as shading, ultrasound, and micro-current, are relatively easy to operate and control and do not introduce other chemicals into the treatment; thus, they can inhibit algal growth at an early stage. Physical methods have the advantages of mild reaction conditions, fast reaction speeds, safety, and economy. They have broad prospects for development and application, especially for drinking water sources with high water-quality requirements. This is the case during algal prevention and control in the transfer of the large-scale South-to-North Water Diversion Project in China, which poses a risk of abnormal proliferation of algae in the canals, which threatens the safety of water supply and affects the stability of water quality. However, the principles of physical prevention and control technologies for algal blooms require in-depth investigation. In particular, equipment used for physical methods should be more designed and applied in engineering. Therefore, this study focused on the principles, effects, and application progress of some algal physical control technologies.

PROGRESS IN THE RESEARCH AND APPLICATION OF TYPICAL PHYSICAL PREVENTION AND CONTROL TECHNOLOGIES FOR ALGAE

Physical shading

Algae are highly sensitive to light and regulate their growth and reproduction based on changes in light intensity and timing, as discussed in foregoing section. Physical shading can prevent nutrients from being absorbed by algae, thereby affecting their reproduction and growth. Physical shading occurs via an alteration of the light illuminance of water such that the algae cannot meet their photosynthesis requirements. Thus, the purpose of inhibiting the growth of algae is achieved; the critical algal inhibition mechanism is shown in Figure 5. Photosynthesis in algae under light irradiation can be expressed using Equation 11. Photosynthesis involves reactions that occur in the presence of light as well as enzymatic reactions that do not require light (dark responses).

$$nCO_2 + 2nH_2O \rightarrow n(CH_2O) + nO_2 + nH_2O \qquad \text{(Equation 11)}$$

Algae can regulate their position in water through the synthesis and rupture of gas vacuoles as well as the synthesis and consumption of carbohydrates. This buoyancy-regulation is believed to play a key role in algal blooms formation. Illuminance can affect the synthesis of chlorophyll-a (Chl-a) and the activity of enzymes. Changes in illuminance alter the rate of photosynthesis, which in turn affects the carbohydrate content of algal cells and the vertical migration of algae. Algae tend to float together under low-light conditions, whereas proliferation is inhibited. When the light level exceeds the light saturation point of photosynthesis in algae, the change has little effect on the intensity of algal photosynthesis. If the illuminance is too strong, photosystem I (PSI) and photosystem II (PSII) of the algal cells are damaged, causing photoinhibition. Under this condition, the photosynthetic rate of algae would no longer increase or may even be weakened and stopped,[66] and the content of dissolved oxygen in the water would also decrease.

Table 1. Advantages and disadvantages of algal prevention and control techniques and their applicability (where UV: ultraviolet)

	Algae prevention and control technology	Advantages	Disadvantages	Application
Physical method	Mechanized salvage	Simple operation, not easy to cause pollution	Low efficiency, high energy consumption, limited eradication and ecological restoration of algal blooms	Works only after algal blooms
	Direct filtration	Higher removal rate	Unable to remove large-scale algae, easily pollutes water	When algal cell density and water turbidity are low
	Air flotation	Strong adaptability, short residence time, saving coagulant	Difficulty in treating algal sludge with high organic concentration discharged	Not suitable for high turbidity water with a lot of sand impurities
	UV	Convenient, no by-products, high efficiency	High power consumption, and damaged microorganisms will partially recover after exposure to visible light	More suitable for small doses of algae-containing water
	Ultrasonic	Efficient, fast, simple, no secondary pollution	Relatively high power consumption	Almost all algae-containing water
	Micro-current	Small voltage, low energy consumption, no secondary pollution	When the electrolysis time is short and the current density is small, the algae are not wholly inactivated	Suitable for the early stages of algal blooms
	Shading	Lower cost, easily operate, better results	Higher input costs, impact on the aesthetics of water, easy to cause pollution	Use before an algae blooms
Chemical method	Pre-oxidation	Remove algae, reduce turbidity in water	High cost, generation of disinfection by-products, affect the ecological environment of water	Not suitable for high water quality requirements
	Algae removal agent	Better results, easy to operate	Secondary pollution, interfering with biological communities, and disturbing the ecological balance	Not suitable for high water quality requirements
	Activated carbon adsorption	High algae removal rate	Long time	Season of high eutrophication
	Modified clay	High algae removal rate	More complicated to operate	Suitable for freshwater algal blooms
Biological method	Aquatic biological control	Better results	Destroying ecosystems and disrupting food chains	Emergency treatment of unsuitable algae
	Aquatic plant control	Low cost	Long time, slow results	Emergency treatment of unsuitable algae

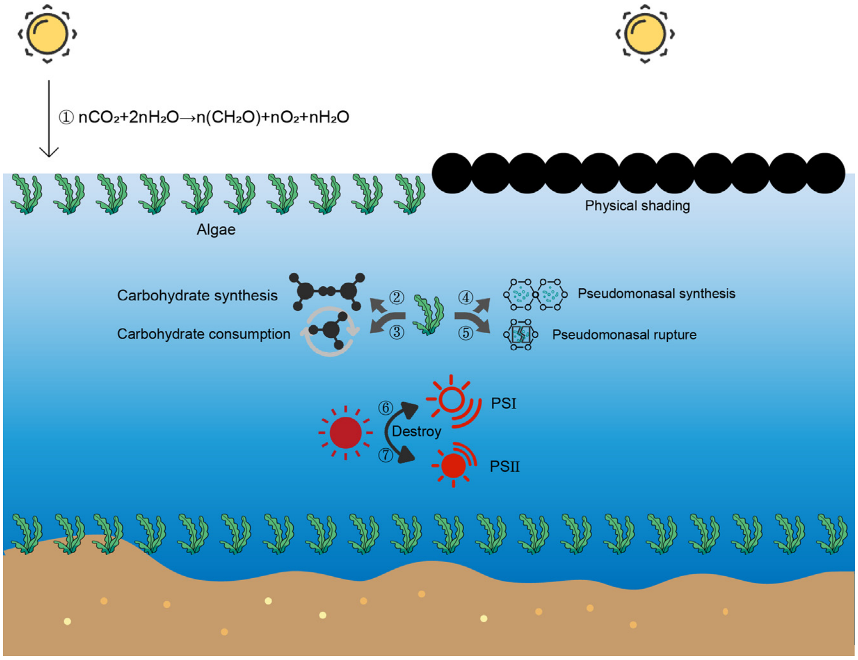

Figure 5. Mechanism of the inhibition of algal growth by shading (① is the photosynthesis of algae, ② to ⑤ are the buoyancy regulation mechanism of algae, and ⑥ and ⑦ are the PSI and PSII of microalgae cells that are destroyed by too high illumination, where PSI: PhotosystemI, and PSII: PhotosystemII)

During physical shading, photosynthetic activity on the surface of algal cells is inhibited and gradually reduced.[67] When cells are exposed to this environment for a certain period, their cell membranes and organelles become damaged, while internal energy reserves and nucleic acid content decrease.[68] As the duration of shading increases, the morphology and structure of the algal cells also changed; as the cell volume decreased, the cytoplasm becomes thicker and the number of organelle decreases. These changes lead to a decrease in cell metabolism and division capacity, ultimately leading to cell death. In addition, shade affects the respiration and photosynthesis of algal cells.[69] During shading, the concentration of oxygen inside cells gradually decreases and the concentration of carbon dioxide gradually increases, leading to an inhibition of cellular respiration and a decrease in energy supply. The nutrient supply within the cell is also affected by photosynthetic inhibition.

Several studies have reported the inhibition of phytoplankton growth by light control or a combination of light control and other factors.[70,71] For example, physical shading has been used to control phytoplankton in drinking water sources.[72,73] Kojima[73] invented a "partial shading method" for small reservoirs used for agricultural irrigation. The possibility of controlling phytoplankton growth by shading more than 90% of the shaded area was also suggested by Chen et al.[74] However, plastic shading materials may lead to microplastic pollution, which poses a risk to water quality, aquatic animals, and human health.[75] The dynamic relationships between shading area, efficiency, and cost must be considered when evaluating the effectiveness of shading and algal control technologies. There are still limitations in this technology, which are reflected in the spectral adjustment, material selection, environmental adaptability, and cost control. Therefore, it is important to further explore reasonable shading areas and times, as well as high-quality, non-polluting shading materials for water, especially drinking water, in future research. For example, new materials manufactured using nanotechnology have better chemical stability and durability and can maintain the effect of light and algal suppression for a long time in harsh environments.

Ultrasonic technology

Ultrasound (sound waves with frequencies higher than 20 kHz) can lead to the structural and functional disruption of algal cells.[76] Ultrasonic waves play a role in water pollution control, mainly because of their cavitation effects on algal cells and the surrounding water.[77] However, after moderate ultrasonic treatment, algal cells can restore their normal physiological functions within a short period. Although there is a certain degree of reversibility in the process of ultrasonic damage to algal cells, excessive ultrasonic treatment can cause irreversible damage, and even lead to cell death. The possible mechanisms by which ultrasound restrains the growth of algae or kills them included the disruption of cell walls, air cells, and active enzymes,[78] as shown in Figure 6.

Ultrasound penetrates the cell wall and causes pressure changes resulting in small molecular movements within the cell.[79] This molecular movement may lead to changes in the cell morphology or even cell rupture. In addition, these pressure waves may affect chemical reactions occurring inside the cells, disrupt the chemical balance inside the cells and, thus, cause further damage to the cells. High-intensity ultrasonic

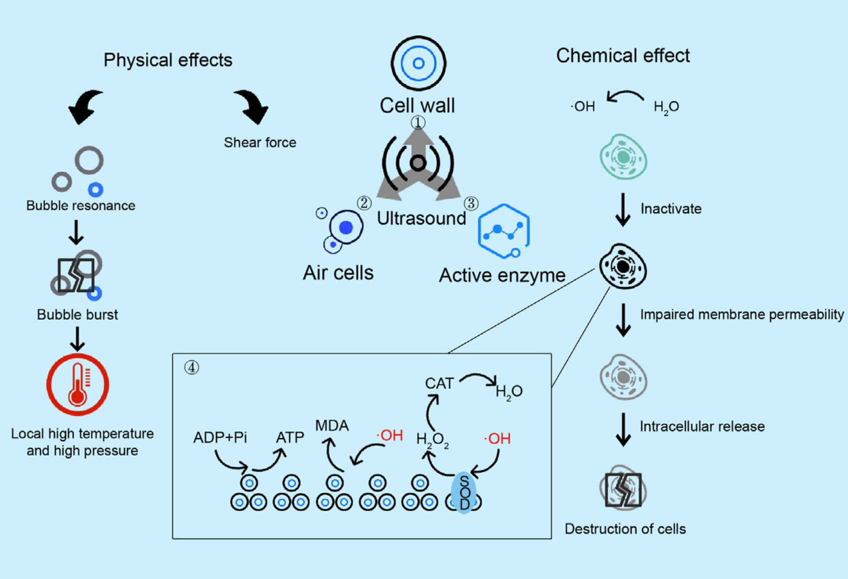

Figure 6. Possible mechanisms of ultrasonic waves on the inhibition of algal growth (where ①∼③ are the destruction of the cell wall, demolition of air cells, and destruction of active enzymes by ultrasonic waves, respectively, and ④ is the destruction process inside the cell)

waves can damage the cell walls of living organisms and cause an outflow of intracellular materials. Shock waves, jet streams, and radiation pressure caused by ultrasound may destroy air cells within algae.

Meanwhile, the high temperature and pressure generated by cavitation, with a large number of free radicals, can destroy active enzymes and active substances within algal cells, thereby affecting the physiological and biochemical activity of the cells. This causes the cellular fluid to disperse, destroying the integrity of the liquid structure and forming tiny bubbles or cavitation nuclei. Millions of bubbles implode, resulting in localized temperatures of up to 5000°C, pressures of up to 100 MPa, and the generation of free radicals.[80] Studies have shown that ultrasound inhibits algal growth by rupturing or collapsing vesicles via cavitation. The destruction of cell walls and membranes interrupts photosynthesis, inhibits cell division and the cell cycle, and reduces the growth rate of algae.[81]

As the effectiveness of ultrasonic algal suppression depends largely on ultrasonic factors, the experimental conditions of ultrasonic treatment must be carefully considered.[82] Studies on the effect of frequency have shown that ultrasound is more effective in inhibiting algal growth at mid-frequencies.[77] In addition, lower frequencies are desirable because they consume relatively less power and may reduce the risk of algal toxin release.[77] It was reported that the algal toxin content can be maintained within 1 μg/L after treatment.[83] In addition, different species of algal cells respond differently to ultrasound, possibly due to the different structures and compositions of algal cells.[84] It was found that ultrasonic waves (28 kHz, 1200 W) could destroy algal cells, causing the algae to sink and die because they could not photosynthesize.[85] Field experiments and laboratory studies have shown that the parameters used for the application of ultrasonic technology are generally in the frequency range of 28–500 kHz, power range of 20–1200 W, impact radius of 150–300 m, or even as high as 12500 m^2, and algal removal efficiency of 30–94%. However, owing to differences in the parameters used, the final effect varies greatly. Therefore, in the application of ultrasonic waves to inhibit the growth of algae and control algal blooms, attention should be paid to the matching of parameters and application conditions, as well as to the inhibition of dominant algae. Currently, there are limitations to ultrasonic algal suppression technology, such as high water quality requirements and the need for the regular replacement of the sound sources. In the future, the combination of ultrasonic algal suppression technology with other technologies, such as photocatalytic technology and biotechnology, will help realize a more comprehensive and effective algal suppression effect.

Micro-current

The inhibition of the growth of algae by micro-current involves the use of a small current, such as 15 mA/cm^2, in the early stage of algal growth and reproduction to inhibit the growth of algae. Growth is controlled within a specific range and intensity to prevent blooms.[86] When a micro-current acts on algal cells, it causes changes in the charge inside and outside the cell membrane, altering the cell membrane, which affects the metabolism and function of the cell. Micro-current electrolysis has both direct and indirect oxidizing effects, and some possible mechanisms involved in the inhibition of algal growth are shown in Figure 7.

Indirect oxidation is caused by active chlorine and active oxygen produced by chlorinated water. Indirect oxidation caused by active chlorine plays a significant role in this process. Direct oxidation involves an electric field on the cell electric breakdown, which affects the cell metabolic function, and electrode electron exchange with the algal cells adsorbs to the electrode surface, resulting in the oxidation of intracellular

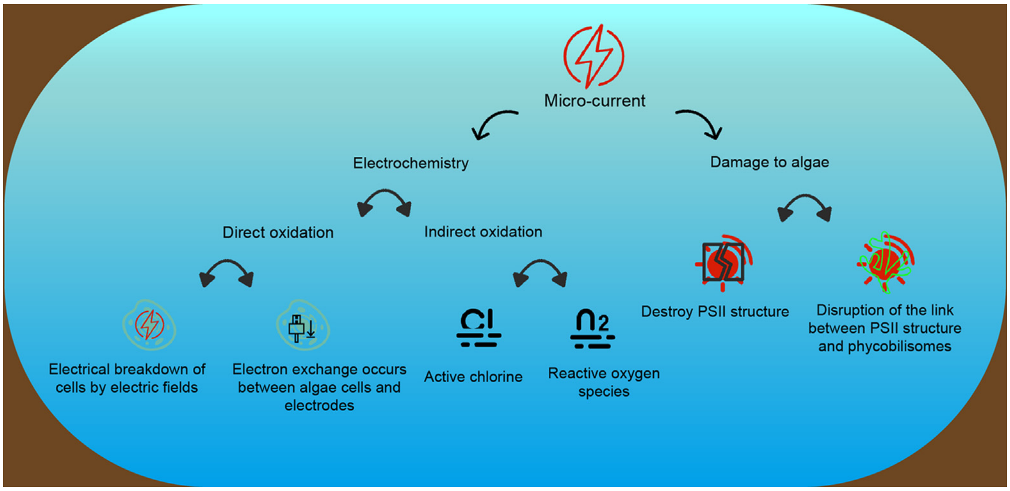

Figure 7. Mechanism of micro-current for the inhibition of algal growth (where PSII: Photosystem II)

enzymes, making the cell inactive.[87] The algal damage caused by micro-current electrolysis includes various aspects of damage to the algal cell structure and enzymatic activity. Micro-current electrolysis disrupts the PSII structure of algal cells, ultimately leading to cell death.

The mechanism of action of micro-currents on algal cells is the regulation of signal transduction within the cells. When micro-currents stimulate algal cells, a series of electrochemical reactions occurs, changing the ion concentration and potential gradient within the cells, thereby affecting the activity of signaling molecules within the cells.[88] After these signaling molecules are activated, they participate in cell metabolism, growth, and development. Meanwhile, micro-currents affect the permeability of the cell membranes, promote the exchange of materials inside and outside cells, and regulate intracellular and energy metabolism, thereby affecting the growth and metabolism of algal cells. The damage mechanism of micro-currents also includes the destruction of the cell membrane structure and the redox reactions of intracellular components.[10] The current flux passing through the algal cell membrane can change the microstructure of the cell membrane, causing edema and rupture, resulting in the outflow of cell content.

Micro-current electrolysis has little impact on aquatic organisms and other components of water bodies.[88] For example, a ruthenium titanium electrode, which is corrosion-resistant and conducive to chlorine precipitation, was used as the anode for the electrolysis of *M. aeruginosa*. The results showed that micro-currents had good killing and inhibition effects on *M. aeruginosa* at an electrolysis time of 15 min and a current density of 10 mA/cm^2.[10] Electrolysis time and current density are likely key factors affecting the inhibition effectiveness of algae. It has also been shown that algal cells can continue to grow and reproduce after light culture if the electrolysis time is shorter and the current density is lower. Generally, extending the electrolysis time and increasing the current density increases the amount of active substances produced by electrolysis, and the effect of algal inhibition will also be enhanced.[89] Zhang et al.[90] experimentally demonstrated that active chlorine produced in water by electrolysis can remove algal toxins. These results demonstrated the feasibility and high efficiency of micro-current technology for algal prevention and control. However, this technology faces many problems and challenges, such as the precise control of current delivery and an impact on aquatic organisms, which need to be further researched and solved. In the future, micro-current algal inhibition technology can be also combined with other water treatment technologies to form a more efficient and comprehensive water treatment program.

UV irradiation

In recent years, UV technology has been used to prevent and control algal infections. The main target molecules acted upon by UV light include nucleic acids, proteins, membrane liposomes, the cytoskeleton, and photosynthetic cells (Figure 8). The most important effect of UV irradiation on the growth and reproduction of algae is on DNA molecules, which results in photochemical reactions of nucleic acids. UV irradiation causes photochemical reactions in nucleic acids, interfering with base pairing, resulting in blockage of DNA replication and the inability to carry out the cell cycle, leading to the inability of algae to reproduce or die. This prevents the transcription of the D1 protein and phycocyanin, which not only disrupts the photosynthetic system but also damages the cell membrane.[91,92] In addition, UV irradiation significantly reduces the contents of the D1 protein and pigments. This damage affects the acquisition of light energy and photochemical processes, which in turn affect photosynthetic and metabolic processes.[92–94]

When algae are exposed to UV radiation, their ribosome-binding sites are altered by UV radiation, making it difficult for ribosomes to continue assembling proteins, which inhibits cell growth and division.[95] UV radiation can induce chemical reactions of lipids on the cell membrane, forming photochemical products such as free radicals and hydroperoxides.[96] These products can destroy the structure and function of the cell membrane, increase its permeability, and cause the leakage of intracellular substances. This ultimately leads to cell death. UV irradiation can also cause intracellular and extracellular microcystin degradation and indirect oxidative damage, leading to a loss of cell membrane

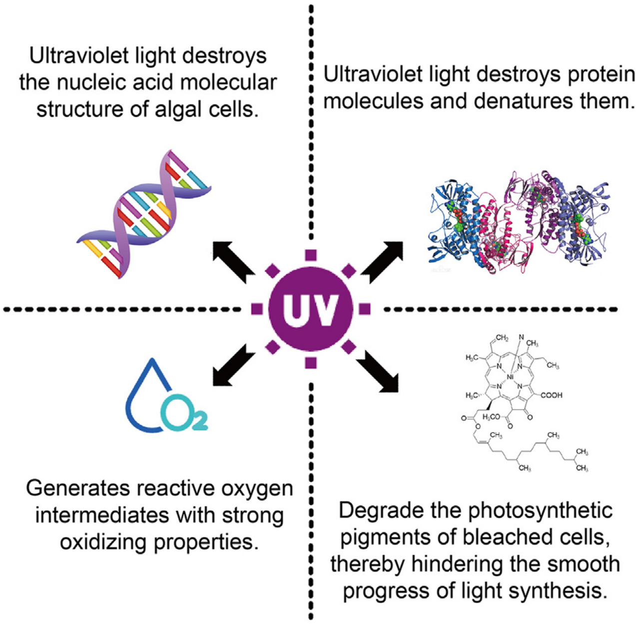

Figure 8. Mechanism of algae prevention and inhibition by UV irradiation (where UV, ultraviolet)

integrity as well as cell death.[97] UV irradiation also degrades Chl-a, disrupts the algal cell photosynthesis system, and damages algal cells. Prolonged irradiation can lead to algal cell lysis,[94] causing the release of intracellular organic matter.

The wavelength of the UV method is a key parameter; thus, choosing an appropriate wavelength enhances the inhibition of algae.[98] The destruction of nucleic acids or microorganisms is determined by the absorption and reaction of nucleic acids or microorganisms to UV light. If absorption occurs without reactions, the UV light at that wavelength will not have an inactivating effect. Shortwave UV radiation can cause microorganisms to produce photochemical products that damage their DNA. This prevents the normal replication of genes, leading to the inactivation of microorganisms and ultimately their death. Different doses of UV irradiation result in varying inactivation effects. High irradiation doses may cause most the destruction of various cellular structures, such as DNA, in most microorganisms, thus making them unable to reproduce. Low doses of irradiation can decrease the reproduction rate of microorganisms for a certain period to maintain stable water quality.[99] UV irradiation can be used to prevent or control algae in static or almost static water bodies, such as landscape water bodies, regulated reservoirs, stagnant harbors, and storage ponds. The technology is still limited; in practical applications, water environments are complex and variable, which would affect the effect of ultraviolet irradiation. Thus, the precise control and optimization design of equipment are required. Intermittent UV irradiation and its use in combination with other preventive and control techniques are important directions for future research and applications.

LIMITATIONS, IMPROVEMENT, AND APPLICATION SCENARIOS

Limitations

The effect of physical shading on algal suppression in the practical application of the project has been verified, but the area of some eutrophic water is too large, resulting in high costs. If the shading range and time control are not reasonable, other harmful microorganisms can easily be produced. Part of the shading material produces other secondary pollutants. Ultrasonic technology is currently mainly limited to landscape water bodies or small-sized waters, with few practical applications in lakes and rivers. Because ultrasonic energy decays rapidly during propagation, it has little effect on algal cells over long distances. Concerns regarding the ecological safety of water have limited the development of this technology. Micro-currents have been investigated and applied less in actual engineering and are currently difficult to apply in some lakes. Because of the need to control the current density and electrolysis time, energy consumption should be considered. Long-term treatment leads to an unstable algal inhibition effect. UV irradiation is used less individually in practical applications because it generates by-products, such as disinfection by-products. Because of the large size of lakes in practical applications, individual UV irradiation devices can only affect the water quality around the device. However, it is difficult to control or treat the algae in a large water area, such as entire lake, significantly. Therefore, it is important to explore further improvements in these technologies and their possible application scenarios.

Improvement measures and application scenarios

Physical shading methods for algal control mechanisms, materials, areas, and adjustment should be further investigated, developed, and applied. Under shading conditions, many water quality indicators of water will respond and change under the influence of algal extinction.

In addition, exploring the combined processes of physical shading, aeration, and water flow separators may further improve the effects of shading and algal suppression. To achieve the best algal removal effect and minimize energy consumption, further research is needed to determine the critical parameters or ranges of ultrasonic control required for different algal species. It is recommended that a combination of low-frequency, hydrodynamic, and UV irradiation be used for algal removal and algal toxin control.[100] The efficiency and effectiveness of the flocculation and sedimentation of damaged or dead algae can be improved by adding coagulants, such as modified clay, after ultrasonic treatment.[101] Regarding micro-current control, current density has a more significant impact on micro-current electrolysis for algal suppression. A higher efficiency can be obtained with a high current density and high circulation flow rate. In future research, the relationship between current density and electrolysis time should be studied in depth to determine the best combination. In addition, other factors, such as hydraulic conditions and temperature, that influence algal control by micro-currents should be further investigated. The combination of micro-currents and biomanipulation may have great potential for algal prevention and control. Further research on the effectiveness of UV light for algal control is essential to evaluate the widespread applicability of this technology.

Each physical control technology has its advantages and disadvantages. There is also a difference in the progress of research, development, and application of actual control technologies and equipment. However, a combination of various physical algal control techniques is likely to obtain an integrated technology that improves the efficiency of algal control and is environmentally friendly. These integrated technologies would disturb the growth of algae in the initial stages and damage the cell structure and DNA of algae during late reproduction. A combination of physical prevention and control techniques could be a future research direction. An intelligent integrated physical prevention and control system should be established for eutrophic water. Intelligent control systems can be developed on the basis of these technologies. Based on algal growth monitoring, individual or joint physical shading, ultrasonic, micro-current, UV, and other prevention and control measures should be implemented. Hydraulics and turbulence are regulated via water conservancy scheduling. However, these control technologies are primarily used in laboratory simulations and have limited practical engineering applications. Therefore, the development of practical engineering application devices and the application of these techniques for the prevention and control of algal blooms are recommended.

The South-to-North Water Diversion Project in China is a global mega water transfer project with three lines: the east, center, and west. As an artificial system, although nutrients such as phosphorus are controlled at a very low level, the South-to-North Water Diversion Project Central Trunk Canal has been characterized by the abnormal proliferation of algae since the opening of the water supply.[102] However, preventive and control methods, such as chemical approaches, which bring about the potential contamination of the drinking water source, are prohibited. Abnormal proliferation of algae in the South-to-North Water Diversion Project can lead to the clogging of the filter media layer, affecting the normal operation of the filtration system and increasing the cost of water production.[103] Thus, the application of physical shading, ultrasound, micro-current, and UV methods alone or in combination has great potential under such scenarios.

CONCLUSIONS

Regarding the effects of physical factors on algal growth and blooms, light is the main factor affecting the photosynthetic activity of algal cells. Thus, changes in the illuminance can have an immediate impact on the vertical migration characteristics of algae. The algal biomass and growth rates increase with increasing temperature until the optimum growth temperature is reached. Under favorable climatic conditions, hydrodynamics, such as scour effects, changes in nutrient flow and uptake efficiency, and algal cell destruction, are key factors affecting algal growth. Operational strategies (e.g., decreased residence time and disrupted stratification) may also impact algal growth.

As a typical physical prevention and control technology for algae, physical shading can inhibit or weaken photosynthesis and inhibit algal growth. Ultrasound mainly destroys cell walls, air cells, and active enzymes, thereby affecting the physiological and biochemical activities of cells. Micro-currents can damage algal cell structures (e.g., PSII) and decrease enzymatic activities through both direct and indirect oxidation, ultimately leading to the death of algal cells. UV irradiation interferes with base pairing by damaging algal DNA, which can lead to the inability of an organism to reproduce or die. In future research, non-polluting water-shading materials should be further explored, and equipment such as ultrasound, micro-current, and UV irradiation should be optimized.

Based on this study, it can be concluded that the development of mechanisms and devices for physical technologies is of great potential for algal prevention and control in the future. A combination of various types of physical technologies would be favorable for algal prevention and control in eutrophic waters. In addition, the establishment of an intelligent integrated physical prevention and control system should be explored to control the growth of algae and damage the cell structure and DNA of algae during late reproduction. This article is of great importance for exploring feasible algal prevention and control measures in specific water bodies such as large artificial trunk canals for the South-to-North Water Diversion in China. However, this article has some limitations in providing specific and effective methods based on specific water bodies. In the future, more relevant data and actual effects should be obtained from engineering projects to better evaluate these physical technologies.

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AUTHOR CONTRIBUTIONS

Y.Y.W.: Writing-original draft and editing, visualization, software, and methodology. Y.R.Z.: Project administration, supervision, writing-review and editing, conceptualization, and funding acquisition. K.W.: validation and investigation. Y.D.T.: Validation and nvestigation. X.J.B.: Formal analysis and data curation. J.J.: Formal analysis and data curation. W.F.: Visualization. L.C.: Software. H.Q.L.: Validation.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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