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Comprehensive Review on Algal Blooms: Characteristics, Causes, Hazards, and Resource Utilization Strategies

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Abstract

Algal blooms, characterized by the rapid proliferation of microalgae or cyanobacteria, pose significant threats to aquatic ecosystems and human health. This review comprehensively examines the characteristics, causes, and hazards of algal blooms, with a particular focus on the environmental conditions that facilitate their formation, such as temperature, light, and nutrient availability. The review also explores various treatment methods for mitigating algal blooms, including physical, chemical, and biological approaches, and discusses the potential for resource utilization of algal biomass. Specifically, the review highlights the extraction of bio-lipids, biofuels, and other valuable products from algal biomass, emphasizing the importance of pretreatment methods to enhance extraction efficiency. The findings underscore the need for integrated strategies that combine environmental management with sustainable resource utilization to address the dual challenges of algal bloom control and biomass valorization.

Keywords: Algal blooms, *Eutrophication, Bio-lipids, Pretreatment methods, Resource utilization, Environmental management*

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Ⅰ. INTRODUCTION

Algal blooms, defined as the explosive growth of microalgae or cyanobacteria under specific environmental conditions, have become a global environmental concern due to their detrimental impacts on aquatic ecosystems and human health[1]. These blooms are often associated with eutrophication, a process driven by the excessive input of nutrients such as nitrogen and phosphorus from anthropogenic sources[2, 3]. The most common species involved in harmful algal blooms (HABs) include Microcystis aeruginosa in freshwater and marine Chlorella species in seawater[3]. The proliferation of these species can lead to severe ecological imbalances, including oxygen depletion, fish kills, and the release of harmful algal toxins that can accumulate in the food chain, posing risks to human health[4].

The increasing frequency and intensity of algal blooms have been linked to climate change and human activities, such as agricultural runoff, industrial discharges, and urbanization[5]. Understanding the environmental factors that contribute to algal blooms is crucial for developing effective mitigation strategies. Temperature, light, and nutrient availability are key drivers of algal growth, with cyanobacteria, in particular, thriving in warm, nutrient-rich waters[6]. The interplay of these factors can lead to the dominance of certain algal species, resulting in the formation of blooms that can persist for extended periods.

In addition to their ecological impacts, algal blooms also present opportunities for resource recovery. The biomass generated during blooms can be harvested and processed to extract valuable products such as bio-lipids, biofuels, and bioplastics. However, the efficient extraction of these products requires effective pretreatment methods to disrupt the robust cell walls of microalgae[7]. This review aims to provide a comprehensive overview of the characteristics, causes, and hazards of algal blooms, while also exploring the potential for resource utilization of algal biomass. By integrating environmental management with sustainable resource recovery, it is possible to address the dual challenges of algal bloom control and biomass valorization.

Ⅱ. ALGAL BLOOM

2.1 Characteristics of Algal Blooms

An algal bloom is an ecological phenomenon characterized by the rapid and excessive proliferation of microalgae or cyanobacteria under specific environmental conditions, leading to detrimental effects on aquatic

ecosystems, human health, and welfare[8]. Among the microalgae species responsible for harmful algal blooms (HABs), *Microcystis aeruginosa* (*M. aeruginosa*) and marine *Chlorella* sp. are prominent in freshwater and marine environments, respectively[9]. The primary consequences of algal blooms include the degradation of aquatic ecosystems, deterioration of water quality, and adverse impacts on aquatic organisms[10]. Furthermore, the release of algal toxins during the lysis and decay of algal cells poses direct and indirect risks to human health through bioaccumulation in the food chain.

Globally, there are approximately 30,000 identified species of algae, of which around 300 are known to form algal blooms, with about 80 species being toxic[11]. Cyanobacteria, particularly *Microcystis aeruginosa*, dominate in terms of both biomass and frequency of occurrence[12]. For instance, in China, lakes such as Anhui's Chao Lake, Yunnan's Dian Lake, and Jiangsu's Tai Lake experience recurrent and severe cyanobacterial blooms annually[13]. In contrast, other algae, such as naked algae, predominantly form red tides in coastal bays[14].

2.2 Causes of Algal Blooms

The frequency, intensity, and toxicity of HABs in coastal and freshwater systems have increased globally, largely due to rising water temperatures and anthropogenic inputs of nitrogen (N) and phosphorus (P)[15]. Cyanobacteria, in particular, exhibit a high degree of adaptability to elevated temperatures and intense light conditions. Strong thermal stratification in water bodies further enhances the likelihood of cyanobacterial blooms[16]. Species such as *Microcystis* and *Anabaena* are often associated with hot, dry climatic conditions and low N:P ratios [17, 18]. In general, the formation of algal blooms is influenced by a combination of environmental factors, including temperature, light availability, and nutrient concentrations.

Temperature: Temperature is a critical factor in the initiation and proliferation of algal blooms. Cyanobacteria, which frequently dominate during summer months, thrive within a temperature range of 20–30°C, with *Microcystis aeruginosa* exhibiting an optimal range of 25–35°C[19]. As temperatures rise, the composition of algal communities shifts, favoring cyanobacteria over other planktonic algae. This is attributed to the superior thermal adaptation mechanisms of cyanobacteria, which enable them to outcompete other algae under high-temperature conditions[6, 19].

Nutrients: Eutrophication, driven by the discharge of industrial, domestic, and agricultural wastewater, is a primary contributor to algal blooms. Nitrogen and phosphorus, derived from these sources, serve as essential nutrients for algal growth. For example, urban domestic wastewater has been found to contain phosphorus concentrations as high as 40.0 mg/L[20]. The influx of these nutrient-rich effluents into aquatic systems provides the necessary conditions for algal proliferation.

Light: Light availability is another critical factor influencing algal bloom dynamics. *Microcystis aeruginosa*, for instance, exhibits high photosynthetic efficiency and a low light saturation point, enabling it to photosynthesize effectively even under low light intensities. However, excessive light can inhibit the growth of certain algae, such as diatoms, which exhibit optimal growth at light intensities of 2000–5000 lx. Light intensities exceeding 8000 lx can significantly reduce algal growth rates, and intensities above 10,000 lx may lead to photoinhibition and cell death. Conversely, prolonged low light conditions can induce algal blooms by promoting rapid population growth over short periods. Studies have demonstrated that *Microcystis aeruginosa* can maintain normal growth under low light conditions by efficiently utilizing available light energy[21].

2.3 Hazards of Algal Blooms

Algal blooms, a hallmark of eutrophication, represent a significant environmental challenge with widespread ecological and public health implications. These blooms lead to the excessive growth of phytoplankton, depletion of dissolved oxygen (DO), and disruption of aquatic ecosystems. The decay of algal biomass can produce noxious odors, release toxins, and cause mass mortality of aquatic organisms. The impacts of algal blooms are multifaceted and can be categorized as follows:

Effects on Aquatic Plants: Algal blooms reduce light penetration and nutrient availability for submerged aquatic vegetation, thereby leading to decreased photosynthetic rates and oxygen production, which adversely affects the growth and development of aquatic plants. Specifically, during blooms, high densities of planktonic algae can accelerate the transition of water bodies to a turbid state, where they become the dominant species and outcompete submerged vegetation[22] . In addition, filamentous algae, which often overgrow in eutrophic waters, can physically interfere with submerged plants through entanglement and chemosensory effects, resulting in their decline [22]. Furthermore, epiphytic algae attached to the stems and leaves of submerged plants can block light and nutrient uptake, thereby inhibiting plant growth and potentially causing decay.

Effects on Aquatic Animals: Algal blooms often form a surface scum that impedes oxygen exchange between the atmosphere and water, thereby creating stratified oxygen conditions[23]. As a result, surface waters become oxygen-saturated, while deeper layers become oxygen-depleted, leading to hypoxic or anoxic

conditions that are detrimental to aquatic life. Moreover, the decomposition of algal biomass consumes substantial amounts of dissolved oxygen (DO), which can trigger hypoxic events such as "pond flooding"[24]. Consequently, these events cause mass mortality of fish and other aquatic organisms due to oxygen deprivation. In addition, toxins produced by harmful algae, such as *Microcystis aeruginosa* and *Anabaena*, can poison aquatic animals and pose health risks to humans and wildlife through trophic transfer[25].

Effects on Water Quality: The decay of algal cells consumes dissolved oxygen (DO) and promotes the anaerobic release of nutrients, thereby contributing to the formation of black, malodorous water bodies[24]. Furthermore, this process releases sulfide and other odorous compounds, which further degrade water quality. In addition, cyanobacterial toxins, such as microcystins, can contaminate water supplies and pose serious health risks if ingested by humans or animals. Specifically, these toxins can cause a range of diseases affecting the liver, nervous system, and other organs through various exposure routes, including ingestion, inhalation, and dermal contact. A notable example of the public health impact of algal blooms is the 2007 drinking water crisis in Wuxi, China, where microcystin contamination left approximately 2 million residents without access to safe drinking water for over a week[26].

Ⅲ. ALGAL BLOOM TREATMENT METHODS

Harmful algal blooms (HABs) are a global environmental concern due to their detrimental impacts on aquatic ecosystems and human health[1]. Strategies for preventing or mitigating HABs primarily include nutrient load reduction, hydrodynamic regulation, chemical algaecide application, biological control through predation or competition, and physical separation or harvesting[27]. Traditional approaches to algal bloom treatment can be broadly categorized into two main methods: harvesting and inactivation of microalgae.

3.1 Harvesting

3.1.1 Single Harvesting Methods

Harvesting refers to the separation or extraction of algae from their growth medium. Current harvesting techniques encompass mechanical, chemical, and biological methods, including sedimentation, filtration, centrifugation, flotation, and flocculation [27]. The choice of harvesting method depends on several factors, such as the physical characteristics of the microalgae (e.g., cell size and density), the desired specifications of the final product, and the feasibility of reusing the culture medium[28].

3.1.2 Mixed-Coupling Harvesting Methods

Coagulation-flocculation-sedimentation (CFS) with liquid ferrate has recently been proposed as a pretreatment strategy for algal bloom remediation [29]. Liquid ferrate enhances the removal efficiency of suspended and colloidal particles, microorganisms, and algal organic matter (AOM)[29] . Studies have demonstrated that liquid ferrate is particularly effective in seawater treatment due to its multifunctional roles as an oxidant, coagulant, and disinfectant. Dissolved air flotation (DAF) is another widely used pretreatment technology for algal bloom control[30-32]. Low doses of liquid ferrate as a coagulant in DAF systems have also been shown to effectively mitigate algal blooms[33].

3.2 Inactivation

3.2.1 Methods and Considerations for Microalgae Inactivation

Various methods have been employed to mitigate harmful algal blooms (HABs) by either limiting favorable conditions for algal growth or directly removing algae from water bodies. These methods include physical approaches (e.g., artificial mixing, ultrasonic radiation, and sediment removal) and chemical approaches (e.g., copper sulfate, diuron, and other algicides) [34]. Chemical algicides are typically non-species-specific, effectively targeting a broad range of algal species [35]. However, physical methods are often energy-intensive and costly, making them less suitable for large-scale applications [34], while chemical methods pose risks of secondary pollution[35]. In contrast, biological methods, such as the use of algicidal bacteria, natural algicidal compounds, aquatic plants, and beneficial phytoplankton, are considered more environmentally friendly and effective for nutrient removal or allelopathic interactions with HAB species [33, 34, 36].

3.2.1.1 Mechanical Methods

UV-C Irradiation: UV-C irradiation (200–280 nm) is a promising method for suppressing microalgal growth and preventing HABs. It induces damage to microalgal cells at multiple levels, including nucleic acids, photosynthetic systems, nitrogen fixation and assimilation, toxin synthesis, cell settling ability, oxidative stress, antioxidative capacity, and cell integrity. The growth suppression effects of UV-C irradiation are typically dose-dependent and often reversible. Key advantages of UV-C irradiation include its chemical-free nature, which minimizes the formation of disinfection byproducts (DBPs) and reduces ecological impacts, as well as the

simplicity and portability of UV-C equipment, making it suitable for large-scale water treatment applications [37].

Copper Ionization: The use of copper (Cu) to treat algal blooms is widely accepted globally. However, the release of Cu into the environment poses potential ecological and health risks. Recent studies have developed a copper ionization cell (CIC) for inactivating bloom-forming microalgae, such as Chlorella vulgaris and Microcystis aeruginosa, in a flow-through system. The CIC enhances microalgae inactivation by increasing cell membrane permeability and promoting excessive Cu uptake. This method offers an environmentally friendly and cost-effective alternative to traditional Cu-based treatments. Notably, the maximum recommended algicidal Cu concentration in water (2 mg/L) exceeds the permissible limits for Cu in drinking water set by global regulatory bodies (e.g., 2.0 mg/L by WHO, 1.3 mg/L by the USA, and 1.0 mg/L by China). The CIC system utilizes Cu mesh electrodes to generate in-situ ionized Cu, providing a sustainable and efficient approach to microalgae inactivation[38].

3.2.1.2 Non-Mechanical Methods

Cold Plasma-Based Oxidation: Cold plasma, generated by combining electrical discharges with gases, is an emerging oxidant for treating algal-impacted waters. A novel approach involves cold plasma-activated bubbles (CPABs), which enhance the interfacial area and residence time of reactive species, improving their transport efficiency. Cold plasma is cost-effective, residue-free, and can be produced using renewable energy sources[39]. During plasma generation, a diverse array of reactive oxygen and nitrogen species (RONS) is produced, including hydrogen peroxide (H_2O_2), ozone (O_3), nitrite (NO_2^-), nitrate (NO_3^-), peroxynitrite ($ONOO^-$), hydroxyl radicals (•OH), and superoxide radicals ($•O_2^-$). These species offer multiple oxidation pathways, making cold plasma a versatile and sustainable alternative to conventional oxidants for degrading algal cells, toxins, and taste/odor compounds[40].

Algicidal Bacteria: Various algicidal bacteria have been isolated for controlling HAB species[36]. These bacteria typically kill algal cells through direct contact or by releasing extracellular algicidal substances. Cell-free supernatants (CFS) derived from bacterial cultures have been extensively studied and shown to effectively control HAB species under laboratory conditions [41, 42]. However, the influence of culture medium on the production of algicidal metabolites remains poorly understood. Additionally, field studies on the algicidal efficacy of CFS and its impact on water quality are limited. The effectiveness of algicidal compounds depends on factors such as compound type, concentration, mode of action, algal cell morphology, and environmental conditions [43, 44]. While algicidal bacteria and compounds can effectively eliminate HAB species, residual nutrients in the water may trigger recurrent blooms.

Microbial Degradation of Algal Cells: Microbial degradation of algal cell walls through chemical or enzymatic actions is another area of interest for algal bloom control[45]. Bacteria play a dual role in aquatic ecosystems, acting as both pathogens that inhibit algal growth and as key agents in nutrient recycling and energy transformation[46, 47].

Ⅳ. PRE-TREATMENT OF ALGAL BIOMASS RESOURCES

Recent research has focused on extracting intracellular materials from microalgae, with effective cell wall disruption being a critical step for low-cost and low-energy extraction[48]. Pretreatment methods, including ultrasonic, microwave, high-pressure, and enzymatic treatments, are essential for achieving this goal.

4.1 Ultrasonic and Microwave Pretreatment

Ultrasonic pretreatment mechanically disrupts microalgae cells through cavitation, facilitating the release of secondary metabolites such as lipids, proteins, carbohydrates, and methane[49]. This method is cost-effective compared to traditional extraction techniques. Microwave pretreatment, on the other hand, ruptures cells by rapidly heating intracellular water, generating high internal pressure. Both methods minimally affect the fatty acid composition of extracted lipids [48].

Studies show that ultrasonic pretreatment at 350–750 W for 5–30 minutes significantly increases lipid recovery, often doubling yields[49]. For instance, ultrasonic treatment boosted lipid yields in Chlorella and Spirulina by 30% and 36%, respectively [50]. Similarly, pulsed microwave energy increased lipid yields from 3.81% to 38.42% when energy input rose from 1.4 MJ/kgDW to 2.8 MJ/kgDW[51]. Microwave pretreatment is generally more effective than ultrasonic methods for lipid extraction[51]. However, combining ultrasound with other techniques, such as low-temperature hydrothermal liquefaction or enzymatic pretreatment, can further optimize lipid yields[52-54].

Ultrasonic pretreatment also enhances bioethanol and hydrogen production. For example, ultrasound-assisted acid pretreatment achieved sugar conversion rates of 98.3% for Chlorella and 99.5% for Spirulina[55], while hydrogen yields reached 0.41 kJ/g after ultrasonic pretreatment[56].

4.2 High-Temperature and High-Pressure Pretreatment

High-temperature and high-pressure methods disrupt microalgae cell walls under extreme conditions. Optimal lipid yields are achieved at 90–120°C with 50–75% sample drying[57]. Ultra-high hydrostatic pressure, a non-thermal method, outperforms high-pressure homogenization, ultrasound, and microwave techniques in cell disruption and lipid extraction rates[58].

For bioethanol production, acid pretreatment at high temperatures and pressures increases reducing sugar yields by approximately one-third, making it suitable for large-scale applications[59]. Similarly, high-temperature and high-pressure pretreatment enhances hydrogen and methane production. For instance, hydrogen yields increased 1.7-fold at 100°C under acidic conditions[60], while methane production rose by 57% with hydrothermal pretreatment[61].

4.3 Acid, Base, and Enzyme Pretreatment

Enzymatic pretreatment, using cellulase, hemicellulase, protease, or pectinase, is environmentally friendly, energy-efficient, and produces fewer byproducts [62-64]. Cellulase is particularly effective for cell wall disruption [65]. Combining multiple enzymes, such as cellulase, xylanase, and pectinase, can increase lipid yields by up to 54.45% [66, 67].

For bioethanol production, enzymatic and acid pretreatments break glycosidic bonds, releasing fermentable sugars. Acid pretreatment, especially with dilute sulfuric acid, is highly effective, achieving an 86% cell disruption rate and nearly tripling carbohydrate release compared to ultrasonic or high-pressure methods[68]. However, enzymatic pretreatment often yields higher sugar and bioethanol production than acid treatment [69, 70].

Enzymatic pretreatment also enhances hydrogen and methane production. Mixed enzyme treatments increase methane yields by 22–162%[71], while the one-step multiple enzyme (OSME) method boosts hydrogen yields by 39.63%[72]. Combining acid or alkaline pretreatment with high-temperature treatment further improves biofuel yields [73].

4.4 Other Pretreatment Methods

The Fenton reaction, recognized for its efficacy in degrading organic pollutants, is also effective in disrupting microalgal cell walls. When combined with hydrodynamic cavitation, it significantly enhances lipid extraction rates, increasing them from 43.1% to 77.4%. However, the extracted lipids often exhibit high viscosity, which may be attributed to residual iron[74]. Electrolytic pretreatment, which utilizes direct current to induce redox reactions, is another method for breaking microalgal cell walls. This approach has been shown to increase hydrogen production rates to 0.43 kJ/g, nearly four times higher than untreated samples[75]. Furthermore, the synergistic combination of electrolysis with ultrasound has been demonstrated to enhance methane yields, reaching up to 257 mL/gVS[76].

Microbial pretreatment leverages bacteria to produce enzymes capable of digesting biomass, offering an environmentally friendly and cost-effective solution. This method has been reported to increase biofuel yields by 22–159%[77]. Additionally, free ammonia pretreatment disrupts the surface morphology of microalgae, thereby promoting biohydrogen production. Under alkaline conditions, this method enhances substrate availability for hydrogen production, achieving yields of up to 22.1 L H2/kg VS[78, 79].

These pretreatment methods collectively contribute to the efficient extraction of valuable compounds from microalgae, while adhering to environmentally sustainable practices. The integration of these techniques into microalgal biomass processing holds significant potential for advancing biofuel production and other biotechnological applications.

V. ALGAL BLOOM BIOMASS RESOURCING

5.1 Biofats and Oils

Biolipids, encompassing fats and lipid-like substances, are essential organic compounds and vital nutrients for human health. Microalgae contain two primary types of lipids: neutral lipids (e.g., triglycerides, sterol esters, and free fatty acids) and polar lipids (e.g., phospholipids and glycolipids), with total lipid content typically ranging from 7% to 20%. This makes microalgae a valuable source of high-quality biofats and oils[54].

Current research highlights several extraction methods for microalgal lipids, including organic solvents, supercritical fluids, ionic liquids, deep eutectic solvents, and solvent-free techniques[54]. Novel methods such as high-shear-assisted extraction[80], vapor recompression with heat integration[81], and water plasma combined with three-phase partitioning have also shown promise[82].

5.1.1 Organic Solvent Extraction

Organic solvent extraction leverages the principle of "like dissolves like" to isolate lipids from microalgae. The Bligh and Dyer method, developed in 1959, remains a widely used technique for rapid lipid extraction from water-rich tissues using a chloroform-methanol-cell suspension ratio of 2:2:8[83]. However, due

to the reliance on toxic solvents, improved methods have been proposed. For instance, hexane extraction after high-pressure pretreatment achieved maximum lipid yields at 90–120°C with a dry biomass-to-water ratio of 50–75%[57]. Ethanol-hexane mixtures following pulsed electric field pretreatment achieved 92% lipid extraction in 2 hours[84], though solvent consumption remains high. Dimethyl ether, combined with ethanol and acetone as entrainers, has been shown to reduce solvent use while maintaining extraction efficiency[85]. Bio-based solvents like ethyl acetate have also demonstrated superior lipid yields compared to hexane, with the added benefit of reducing polyunsaturated fatty acid content in extracts[86]. Deep eutectic solvents, a renewable alternative, have achieved lipid recoveries exceeding 18% compared to traditional methods[87].

5.1.2 Supercritical Fluid Extraction

Supercritical fluids, particularly supercritical CO_2 , are effective for lipid extraction due to their unique gas-liquid properties, which enable high solubility and low environmental impact[88]. Supercritical CO_2 extraction combines extraction and separation processes, yielding safe, non-toxic, and high-purity products[82]. Lipid yields increase with pressure, though mass loss also rises[89]. Temperature effects are pressure-dependent, and the addition of methanol can significantly enhance extraction rates, especially with gradual addition[90]. Novel approaches, such as combining hexane with CO_2 or using CO_2 -responsive deep eutectic solvents (DESs), have shown improved lipid recovery and cyclic stability[91, 92]. Subcritical CO_2 -expanded ethanol extraction has achieved up to 25% lipid recovery, with extracts rich in DHA and antioxidants[93]. Supercritical water gasification has also increased lipid yields by 10.2%[94].

5.1.3 Solvent-Free Extraction

Solvent-free extraction, an eco-friendly alternative, suspends wet microalgae in alkaline solutions followed by high-temperature treatment and centrifugation to separate lipids[95]. This method avoids toxic solvents and biomass drying, making it ideal for sustainable biodiesel production. Hydrothermal pretreatment at 245°C for 10 minutes achieved a 95.0 wt% lipid yield[96], while alkali and heat treatment at 150°C yielded 77.37%[95]. Subcritical water treatment at 260°C with acid-catalyzed esterification achieved 98.4% efficiency[97].

5.1.4 Saponification

Saponification, the reaction of lipids with bases to produce fatty acid methyl esters (FAMEs), is a simple and time-efficient method. For example, acetone-assisted saponification with methanolic potassium hydroxide achieved 98% fatty acid yield[98]. Direct saponification with NaOH/methanol and HCl/methanol esterification reduced reaction times to under 15 minutes[99]. However, this method is unsuitable for extracting polyunsaturated fatty acids, limiting its application[83].

5.1.5 Other Lipid Extraction Methods

Innovative methods, such as high-shear mixing, steam recompression with heat integration[80], and water plasma with three-phase partitioning, have achieved lipid extraction rates of 90%, 52.4% energy savings, and 74.34% efficiency, respectively. These methods are particularly advantageous for high-water-content microalgae, offering short processing times and low costs[82].

5.2 Biofuels

Biofuels, derived from biomass fermentation, are renewable alternatives to petroleum-based fuels. Microalgae, with their high carbohydrate content and ability to grow on non-arable land using brackish water, are promising feedstocks for sustainable biofuel production[100].

5.2.1 Fermentative Microorganisms

Fermentative microorganisms, including yeast and bacteria, play a critical role in biofuel production. Yeast generally yields higher ethanol compared to mixed bacterial cultures[101]. Escherichia coli, widely used for its rapid growth and low cost, produces ethanol but with lower yields due to by-product formation[101]. Dark fermentation for hydrogen production involves hydrolyzing polysaccharides into reducing sugars, which are then converted into hydrogen, CO_2 , and metabolites by hydrogen-producing bacteria like Clostridiaceae and Enterobacteriaceae[102]. Methane production relies on synergistic actions of bacterial and archaeal microorganisms, with hydrolysis, acidification, acetogenesis, and methanation stages[103].

5.2.2 Ethanol Production

Microalgal biomass, rich in carbohydrates, is a viable feedstock for bioethanol. Methods include separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), and simultaneous saccharification and co-fermentation (SSCF)[104]. SHF yields higher ethanol but is prone to contamination, while SSF simplifies the process but is operationally challenging. SSCF, which efficiently

assimilates hexoses and pentoses, offers the highest ethanol yield (24.1%) but at a higher cost[104, 105]. Ultrasonic pretreatment combined with SSF achieved an ethanol yield of 4.27 g/L[104]. Photofermentation and dark fermentation are alternative approaches, with transgenic cyanobacteria showing potential for bioethanol production[106].

5.2.3 Biological Hydrogen Production

Hydrogen, a clean energy source, can be produced via gasification, pyrolysis, photofermentation, and dark fermentation. Supercritical water gasification achieved a hydrogen production rate of 45.3%[107], while dark fermentation, though limited by oxygen sensitivity and thermodynamic constraints, remains widely used due to its low energy demand and high yield[102]. Photofermentation, utilizing direct or indirect biophotolysis, offers cleaner hydrogen production but with lower yields[102].

5.2.4 Methane Production

Microalgal biomass undergoes anaerobic digestion to produce methane, with hydrolysis, acidification, acetogenesis, and methanation stages. Co-digestion with substrates like rice residue or potato processing waste enhances methane yields[71, 108]. Rumen fluid and fungi have also been shown to improve methane production by enhancing hydrolysis[109, 110]. Temperature and harvesting time significantly influence methane yields, with optimal conditions varying by study[111].

5.3 Other Microalgae Resource Utilization Pathways

5.3.1 Feed

Microalgae grown in conventional water resources are nutrient-rich, providing essential vitamins, minerals, and antioxidants, making them valuable as feed[112]. In aquaculture, microalgae reduce ammonia concentrations and improve water quality, offering a sustainable alternative to terrestrial plant feeds[113, 114].

5.3.2 Bioplastics

Microalgae-derived bioplastics, such as polyhydroxyalkanoates (PHA), are biodegradable and renewable alternatives to petrochemical plastics[115]. Species like Chlorella and Spirulina are commonly used, with plasticizers and bulking agents enhancing product quality[116]. Despite their potential, further research is needed to optimize strain selection and production methods for large-scale bioplastic production[117].

Ⅵ SYNERGISTIC HARVESTING AND RESOURSE UTILIZATION

6.1 Adjustment of C/N for microalgae resourcefulness

C/N can regulate the nutrient components of microalgae cells by controlling the synthesis of lipids, proteins, and carbohydrates, and different C/N have different effects on the synthesis of proteins, lipids, and carbohydrates[118]. It has a certain degree of influence on the conversion of lipids and proteins, and high C/N can promote lipid accumulation, while low C/N can glutamate synthesis and therefore promote protein synthesis[119].

Regulation of C/N has a facilitating effect in both microalgal growth and fermentation. In terms of microalgal growth, it has been shown that C/N plays a role in improving lipid quality in microalgae, and the use of organic carbon sucrose and NO_3-N and optimization of C and N ratios using response surface methodology-centered composite design (RSM-CCD) resulted in a 60.34% increase in lipid content[120]. Bio-lipid accumulation reached a maximum of more than 45% of dry weight ratio when C/N reached 110-130[121]. He found that the biomass of Chlorella showed an increase followed by a decrease as C/N increased, so it could be found that the C/N that produced the maximum biomass was 11:1, while the carbohydrate amount reached a maximum at a C/N of 9:1. In addition, the productivity of microalgal biomass was higher at a CN ratio of 5:1[122]. And when the C/N ratio was 12:1, the biological production and protein content could reach higher levels of 0.90 g/L/day and 61.56%, respectively[123].

In microalgal fermentation, for microalgal methanogenesis, C/N also influenced the final methane production to some extent, who increased the microalgal biomass C/N to 7.90 to facilitate subsequent fermentation for biogas production, which was experimentally proven to be beneficial for anaerobic digestion[124]. When performing fermentation for methane production, the use of cationic starch with a C/N of 28.0 can reduce the fermentation time by 22.1%. And the improvement is less costly and does not add significant additional energy[125]. who co-fermented highland section spirochetes with a carbon-rich substrate and adjusted the C:N ratio to 25, could significantly improve the biomass conversion rate[126].

It can be seen that responsive C/N adjustment according to different product requirements can significantly improve the yield and quality of products, which can further promote the feasibility of microalgae resourcefulness. There is still a lack of research on this aspect, and in the future research direction, more corresponding areas can be explored to further optimize the microalgae resourcefulness methods.

6.2 Adjustment of electron donor to promote microalgae resourceization

Microalgae are highly flexible in their response to environmental constraints and are able to change their photosynthetic electron flow capacity[127]. This flexibility may explain why microalgae have high biomass, are one of the major contributors to marine primary biological productivity, and are considered a promising option for biotechnological applications. Microalgae are also capable of altering their photosynthetic electron flow by changing their maximum growth rate and/or shifting photogenerated electrons to different sinks depending on their growth state. It has been shown that total lipid content can be increased by adjusting the salt content of the growth medium, he significantly increased the lipid content by NaCl stress, reaching 32.26%[128]. Reduced the culture pH below 6.5 and added 9.8 mg/L of ferric chloride, which improved the harvest rate of microalgae while reducing the use of coagulants. And the residual iron can be recycled to achieve sustainability of the process[129].

The generation of hydrogen and methane from microalgal biomass by dark/light fermentation and other methods is a green energy yield technology[130]. However, the production of biohydrogen and methane is usually limited at the industrial level. Among the reasons are the presence of oxygen during fermentation and insufficient electron donors in the reactor, which can negatively affect the [Fe]-hydrogenase and methanogenic processes and make them unsuitable for large-scale operations. Electron donors can increase the activity of [Fe]-hydrogenase and improve the efficiency of the overall process. Among these electron donors, Fe and TiO_2 were shown to enhance the enzymatic activity of [Fe]-hydrogenase during biophotolysis for hydrogen production[131, 132]. By supplementing the reactor with electron donors, bacterial degradation of organic matter and methane production could be enhanced simultaneously[133]. It was found that conductive electron donors can improve the electron shuttle between different types of bacterial cells in anaerobic fermentation systems, thus increasing methane production[134]. In addition, electron donors can accelerate hydrolysis by providing a larger surface area to volume ratio for bacterial cells to degrade organic matter[135]. Electron donors can also act as electron donors/acceptors and cofactors for important processing enzymes, leading to significant yield increases.

Ⅶ CONCLUSION AND FUTURE PERSPECTIVES

In conclusion, algal blooms represent a significant environmental challenge, driven by a combination of natural and anthropogenic factors. The increasing frequency and intensity of these blooms highlight the need for integrated management strategies that address both the causes and consequences of algal proliferation. Effective mitigation strategies should focus on reducing nutrient inputs, improving water quality, and developing early warning systems to detect and respond to blooms before they become severe.

At the same time, the potential for resource recovery from algal biomass offers a promising avenue for sustainable development. The extraction of bio-lipids, biofuels, and other valuable products from algal biomass can provide economic benefits while also reducing the environmental impact of blooms. However, realizing this potential requires further research into efficient and cost-effective pretreatment methods, as well as the development of scalable technologies for biomass harvesting and processing.

Future research should also explore the potential for integrating algal bloom management with other environmental goals, such as carbon sequestration and wastewater treatment. For example, microalgae can be used to capture carbon dioxide from industrial emissions or to treat wastewater by removing nutrients and pollutants. These integrated approaches could provide multiple environmental and economic benefits, contributing to a more sustainable and resilient future.

In summary, addressing the challenges posed by algal blooms requires a holistic approach that combines environmental management with sustainable resource utilization. By leveraging the potential of algal biomass as a resource, it is possible to mitigate the impacts of blooms while also creating new opportunities for economic development and environmental protection.

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