Advances in Microalgal Technology for Aquaculture Wastewater Treatment

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ABSTRACT

With the rapid expansion of the global aquaculture industry, the treatment of aquaculture wastewater containing nitrogen, phosphorus, antibiotics and other pollutants has become a critical factor restricting the industry's sustainable development. Physical, chemical and biological treatment methods are currently the mainstream technical routes for aquaculture wastewater treatment, yet each has inherent limitations such as high costs, secondary pollution and poor adaptability to complex water quality. As a green biological treatment technology, microalgal treatment has attracted extensive research attention due to its advantages of low operational cost, high pollutant removal efficiency and no secondary pollution. This paper systematically elaborates on the core mechanisms of microalgae in aquaculture wastewater treatment, including the targeted assimilation and removal of nitrogen and phosphorus through photosynthesis and metabolic regulation, the synergistic degradation of complex pollutants by microalgae-bacteria symbiotic systems, and the regulatory effects of key environmental and process factors on treatment efficiency. It further summarizes the construction of microalgal technology systems for aquaculture wastewater treatment, involving the screening and directional optimization of core algal strains, the comparative analysis of mainstream treatment technologies, and the innovation of microalgae-based coupling technologies. Additionally, the paper identifies the current technical and economic bottlenecks faced by the practical application of microalgal treatment technology, such as poor environmental adaptability, unstable system operation, high initial investment and immature biomass resource utilization. Finally, the future development directions are proposed, including the precise optimization of microalgal strains and process parameters, the high-value resource utilization of microalgal biomass, and the integration of synthetic biology, artificial intelligence and other cutting-edge technologies to promote the development of microalgal treatment systems towards high efficiency, intelligence and sustainability. This study provides a comprehensive theoretical basis and technical reference for the green governance and resource utilization of aquaculture tailwater.

Keywords: Aquaculture Wastewater; Microalgal Treatment; Nitrogen and Phosphorus Removal; Microalgae-Bacteria Symbiosis; Resource Utilization; Sustainable Development.

1. INTRODUCTION

In recent years, with the gradual improvement in living standards, the demand for aquatic products has increased substantially, leading to the continuous expansion of the aquaculture industry all over the world. During aquaculture operations, excessive external inputs such as feed are often introduced into aquatic systems. Consequently, aquaculture wastewater typically contains residual feed, fecal matter, veterinary drug residues, organic debris, and suspended solids [1][2]. Therefore, the treatment of aquaculture wastewater has become a key challenge for the sustainable development of the global aquaculture industry, as such effluents contain a variety of pollutants, including organic matter, suspended solids (SS), nitrogen and phosphorus nutrients, and antibiotics [1][3][4]. Therefore, the development of efficient technologies for aquaculture wastewater treatment is of great importance.

Aquaculture wastewater treatment methods are generally categorized into three types: physical, chemical, and biological. Physical treatment uses physical processes to remove nutrients (e.g., nitrogen, phosphorus), suspended particles and some organic pollutants, being simple and effective for particulate matter and colloids. For example, HS-BF systems remove solid particles [5], while activated carbon or biochar adsorbs antibiotics and reduces ARG accumulation [6][8][9]. It has high operational costs and complex maintenance. Chemical treatment removes nitrogen via chemical reactions with high efficiency, but is limited by small scale, high costs and potential secondary pollution. A laboratory study showed BAFs removed over 90% of sulfonamide and tetracycline antibiotics, with biodegradation, adsorption, nitrification and denitrification as key mechanisms [10].

As a widely used approach, biological treatment converts inorganic nitrogen into N_2 to reduce eutrophication. Some microbial systems degrade specific antibiotics, but antibiotics may affect microbial EPS and treatment efficiency [9]. Microalgae possess strong adsorption capacity and the ability to degrade organic pollutants and heavy metals, as well as high tolerance to environmental conditions, which makes them widely applied in wastewater treatment. As a type of biological treatment technology, microalgal treatment systems have attracted considerable attention due to their advantages such as low investment cost, simple operation, and significant pollutant removal efficiency. Owing to their rapid growth, ability to simultaneously remove multiple pollutants, and strong capacity for heavy metal adsorption, microalgae have become an important focus in wastewater treatment research. Their characteristics of high efficiency, low operational cost, and absence of secondary pollution not only reduce environmental burdens but also promote resource recycling and sustainable management.

2. MICROALGAE TREATMENT TECHNOLOGY

Microalgae technology mainly removes nitrogen and phosphorus from water through biological absorption. Microalgae can directly absorb ammonium nitrogen, nitrate nitrogen and nitrite nitrogen in water and turn them into a part of their own bodies, such as protein, nucleic acid and chlorophyll, thus fixing the nitrogen in water into biomass [12] [13]. At the same time, the photosynthesis of microalgae will increase the pH value of the surrounding environment, which can promote ammonium nitrogen to be converted into free ammonia and then volatilized, thus improving the efficiency of treating wastewater with high ammonia nitrogen [14] [15] [16] [17] [18].

In the system where algae and bacteria live together, microalgae will provide oxygen and release some organic matter, which can help complete the nitrification and denitrification process and make the removal effect of total nitrogen better [19] [20]. Besides removing nitrogen and phosphorus, this symbiotic system of algae and bacteria has many other abilities, such as adsorbing heavy metals, partially degrading organic pollutants, fixing nitrogen, and producing extracellular polymers (EPS). Moreover, the biomass produced in the treatment process is also very useful, which can be used to produce biodiesel, animal feed, pigments, antioxidants and fertilizers, so that the high-value recovery and utilization of biomass can be realized [19] [21] [22].

3. CORE MECHANISMS OF MICROALGAE FOR REMOVING AQUACULTURE WASTEWATER

3.1 Mechanism of Targeted Removal of Nitrogen and Phosphorus

The core mechanism of microalgae removing nitrogen and phosphorus from aquaculture wastewater is related to their own photosynthesis and nutritional needs. Microalgae will absorb nitrogen and phosphorus in wastewater, and then transform them into organic nitrogen compounds such as protein and nucleic acid through intracellular enzymes and secreted enzymes, thus realizing biological nitrogen fixation. Specifically, nitrate nitrogen and nitrite nitrogen will become ammonium nitrogen under the catalysis of nitrate reductase and nitrite reductase, and then be assimilated into amino acid metabolism network through GS/GOGAT pathway or glutamate dehydrogenase [12]. In the practical application of nitrogen removal from wastewater by microalgae, different algae will have different nutrient removal efficiency and adaptability to the environment, which will affect the treatment effect and overall value. For example, Spirulina and Chlorella can not only effectively remove nitrogen and phosphorus, but also accumulate high-value biomass such as protein and fatty acids, making the economic value of wastewater treatment higher [13]. Under suitable lighting conditions, microalgae will carry out photosynthesis, release oxygen, and provide necessary oxygen for other biological treatment processes in wastewater. In addition, the photosynthesis of algae will consume H+ ions in wastewater, change the pH value of water, and form a weak acid environment. This helps to release ammonia into the atmosphere, thus reducing the nitrogen content.

The directional removal of phosphorus by microalgae is a complex biological process, which is controlled by molecular regulation, intracellular storage and systemic metabolism. Its core mechanism is to actively absorb phosphorus and transform it into stable biomass. At the molecular level, when the concentration of inorganic phosphorus in the environment decreases, microalgae will activate the phosphorus hunger response (PSR) system. Under the regulation of transcription factors such as PSR1, the expression of high affinity phosphate transporters is up-regulated, thus enhancing the active absorption capacity of H2PO4-/HPO42- [14]. In addition, microalgae can secrete alkaline phosphatase (APA) and hydrolyze soluble organic phosphorus (ATP) into inorganic phosphorus for use, so that more kinds of phosphorus sources can be utilized [23] [24]. At the cellular level, the absorbed phosphorus will be quickly converted into polyphosphate(polyP) by enzymes such as polyphosphate kinase (PPK), and then stored in vacuoles or granular structures [25].

This process can not only keep the absorption pressure difference inside and outside the cell membrane, but also realize high-density phosphorus enrichment. When Chlorella undergoes phosphorus deficiency pretreatment, it will greatly activate this “luxury absorption” mechanism, and make them show higher removal rate when they regain phosphorus supply [26]. At the whole system level, phosphorus metabolism is linked with carbon and nitrogen cycle, and regulating iron and organic carbon sources can indirectly improve phosphorus removal effect [27]. In the microalgae-fine bacteria symbiotic system, nutrient circulation and oxygen exchange further improve the overall removal capacity [28] [29]. Therefore, microalgae phosphorus removal is a targeted enrichment process driven by gene regulation and supported by metabolic network, which provides an important theoretical basis for sewage treatment and phosphorus resource recovery.

3.2 Synergistic Degradation of Complex Pollutants

The core mechanism of microalgae removing nitrogen and phosphorus from aquaculture wastewater is mainly related to their photosynthetic activities and physiological needs for nutrition. Microalgae absorb nitrogen and phosphorus from wastewater into their own cells, and then turn them into intracellular organic nitrogen compounds, such as protein and nucleic acids, through the action of intracellular and extracellular enzymes, so that biological nitrogen fixation can be realized. Specifically, nitrate and nitrite must be reduced to ammonium under the catalysis of nitrate reductase and nitrite reductase respectively. The produced ammonium will then be assimilated into the amino acid metabolism network through GS/GOGAT pathway or glutamate dehydrogenase pathway [12].

When using microalgae to treat nitrogen in wastewater, different algae have different abilities to remove nutrients and adapt to the environment, which will affect the treatment effect and the value of the whole process. For example, Spirulina and Chlamydomonas can effectively remove nitrogen and phosphorus, and at the same time, they can accumulate high-value biomass such as protein and fatty acids, making wastewater treatment more profitable [13]. Under proper illumination, microalgae will carry out photosynthesis and release oxygen, which can help other biological treatment processes in wastewater system. At the same time, photosynthesis will consume H in water, change the pH value of water environment, and make water weakly alkaline, so that ammonia can easily volatilize into the air, thus reducing the nitrogen concentration in water. When treating complex pollutants, antibiotics and pharmaceutical residues should also be considered. Oxytetracycline and norfloxacin can affect microbial extracellular polymeric substances (EPS) during biological denitrification of aquaculture wastewater [11]. Moxifloxacin may inhibit the growth, photosynthesis and metabolic activity of cyanobacteria under different phosphorus levels [34]. Meanwhile, different microalgae-based technologies show varying antibiotic removal performance under multiple antibiotic concentrations [35]. In addition, microalgal-bacterial consortia and alga-activated sludge combined systems have been reported to remove pharmaceutical pollutants such as ketoprofen and cephalosporins [36] [37].

Phosphorus removal by microalgae is a complex biological process, which includes molecular regulation, intracellular storage and metabolism of the whole system. The core mechanism is that microalgae will actively absorb phosphorus and transform it into stable biomass efficiently. At the molecular level, when the concentration of inorganic phosphorus in the environment decreases, microalgae will start the phosphorus hunger response system. Under the regulation of transcription factors such as PSR1, the expression of high affinity phosphate transporters will increase, thus enhancing the active absorption of H2PO4- and HPO42- [14]. At the same time, microalgae can also secrete alkaline phosphatase, which can hydrolyze dissolved organophosphorus compounds, such as ATP, into inorganic phosphate for utilization, thus expanding the range of available phosphorus sources [23] [24].

At the cellular level, phosphorus absorbed by microalgae will be rapidly transformed into polyphosphate (polyP) under the catalysis of polyphosphate kinase (PPK) and other key enzymes, and then stored in small bubbles or granular structures in cells [25]. This intracellular change can not only keep the concentration difference needed for algae to absorb phosphorus continuously, but also enable algae cells to enrich phosphorus efficiently. In particular, if microalgae are starved for a while (without phosphorus), this “over-absorption” mechanism can be effectively activated; In this way, when there is phosphorus in the water again, the phosphorus removal efficiency of Chlorella will become particularly high [26]. From the metabolic point of view of the whole system, the phosphorus metabolism of microalgae is closely related to the carbon and nitrogen cycle in water. Adjusting the amount of iron ions in water and the supply of organic carbon sources can indirectly improve the efficiency of phosphorus absorption and removal by microalgae [27]. In the microalgae-fine bacteria symbiotic system, nutrient circulation and continuous oxygen exchange between different species can make the whole system more capable of removing phosphorus [28] [29]. Simply put, microalgae phosphorus removal is a precisely controlled process, which is driven by the gene regulatory network in cells and based on various systemic metabolic pathways, which lays a solid theoretical foundation for microalgae to be used in aquaculture wastewater treatment and phosphorus resource recovery.

3.3 Regulation of Key Influencing Factors

illumination intensity

According to the current research, the light intensity must be kept in a suitable range. Too strong or too weak will affect the key metabolic processes of microalgae, such as fixing CO2, producing O2 and synthesizing chlorophyll, thus inhibiting their physiological activities [7]. The results showed that the growth rate, photosynthetic pigment synthesis and nitrogen removal capacity of Chlorella pyrenoidosa would increase with the increase of light intensity in the range of 3000-7000 Lux. However, if the light reaches 9000-11000 Lux, these indexes will decrease, and the enzyme activities related to nitrogen metabolism will be obviously affected by the light intensity [38].

Similarly, Chlorella sorokiniana cultured under different light intensities (22, 68 and 162 mol m-2 s-1) also showed that light intensity would significantly affect its growth rate and its ability to remove nutrients (compounds containing nitrogen and phosphorus). Therefore, suitable lighting conditions can improve the removal efficiency of nutrients [39].

Light duration

Light can stimulate some microalgae to absorb nitrate. Although photoperiod will affect the absorption of nitrate by microalgae, the change of light-dark cycle will also affect the biochemical composition of algae cells. Li S. et al. studied the treatment of mariculture wastewater by bacteria-algae coupling reactor under different photoperiods. Their research shows that photoperiod significantly affects the growth and photosynthetic activity of Chlorella vulgaris, and its removal efficiency of NH4+-N and total phosphorus (TP). Usually, the best effect is observed under moderate light-dark cycle (such as 12L:12D) [38]. Higher illumination ratio (prolonging photoperiod) can enhance the transfer and storage of phosphorus by microalgae. However, when the illumination time exceeds about 16 hours, inhibition may occur, thus negatively affecting the phosphorus removal efficiency [40].

PH

In liquid culture, after algae cells absorb inorganic nutrients (such as nitrogen and phosphorus), their utilization efficiency will be greatly affected by pH value. Most microalgae grow best between pH 7.0 and 9.0. Some microalgae like alkaline environment, such as Spirulina platensis, which can grow at pH 9.0 to 11.0. Dunaliella salina grows best at neutral or weakly alkaline pH, while other green algae (such as Chlorella) prefer acidic conditions. The pH value of the culture medium will not only affect the growth of microalgae and the establishment of symbiotic system [41], but also regulate the formation of biofilm in the process of algae-bacteria symbiosis [42].

Hydraulic Residence Time (HRT)

Treating aquaculture wastewater with microalgae usually uses symbiotic systems or reactors. In the process of reactor purification, hydraulic retention time (HRT) is a key parameter, which directly affects the treatment effect. Xinzhen Wang used the tolerant Chlorella strain isolated from landfill leachate to do the purification experiment of pig farm wastewater [43]. The results showed that the removal rates of COD and ammonia nitrogen in all treatment groups were over 90%, and the removal rate of phosphorus was over 60%. Among them, the experimental group with HRT of 18 hours has the most comprehensive treatment effect. In the study of treating synthetic mariculture wastewater with mixed microalgae, the removal rate of ammonia nitrogen increased with the extension of HRT, but the phosphate concentration was the opposite. Although the removal rate of organic matter increased slightly with the extension of HRT, it was less affected by HRT [44]. It is worth noting that the overall treatment effect of 18-hour HRT group is the most obvious. Recent optimization of livestock farming wastewater treatment by algal-bacterial symbiosis also showed that operating parameters such as pH, hydraulic retention time and nutrient conditions jointly affect pollutant removal efficiency [76].

Types and concentrations of pollutants

Types and concentrations of pollutants Pollutant concentration is another important factor affecting microalgae-based wastewater treatment. Increasing concentrations of oxytetracycline and enrofloxacin can influence algal growth and the sewage purification performance of algal-bacterial consortia [45]. In addition, the treatment performance of Chlorella vulgaris, Neochloris oleoabundans and mixed indigenous microalgae differs among primary effluent, secondary effluent and centrate, indicating that pollutant load and wastewater type directly affect microalgal purification efficiency [46].

Salinity

Salinity has a great influence on the growth of algae and bacteria and all kinds of activities in their bodies [47]. The optimum salinity level of different kinds of microalgae is different. If the salinity in the culture solution changes, it may have a bad influence on the growth of microalgae and biochemical components in the body because of osmotic pressure, ion pressure, or changing the ability of cell membrane to let ions in and out. In addition, salt stress can also interfere with electron transfer in algae photosynthesis and reduce the efficiency of primary photochemical reaction [48,49]. Studies have shown that under 0.75 M NaCl (approximately 43.8 g/L NaCl) stress, the PSII function and photoinhibition sensitivity of halotolerant Spirulina change, with a decrease in photochemical quenching (qP) and an increase in the proportion of QB-non-reducing PSII reaction centers [50]. Under 0.8 M NaCl stress, its photosynthetic oxygen evolution activity and PSII electron transport activity decrease significantly, the efficiency of excitation energy transfer from phycobilisomes to PSII is reduced, whereas energy transfer to PSI is enhanced [51]. As one of the most common approaches for wastewater treatment, algae-bacteria symbiosis technology not only enables algae to remove nitrogen, phosphorus and other organic pollutants, but also greatly enhances removal efficiency through the synergistic interaction between algae and bacteria. The performance of bacteria in wastewater treatment varies under different conditions, and bacterial growth differs at various salinity levels. At a salinity of 3.5%, the dominant bacterial groups in marine anammox bacterial communities include marine actinomycetes, Candidatus Scalindua, and Marinicella. With decreasing salinity, taxa capable of efficiently scavenging reactive oxygen species (ROS) or surviving under anaerobic/microaerobic conditions may become dominant if the redox state of the environment shifts. In addition, salt stress impairs the efficiency of excitation energy transfer from phycobilisomes to photosystem II (PSII), but may enhance energy transfer to photosystem I (PSI) [51]. In the algal-bacterial granular sludge (ABGS) system, with the gradual increase of salinity (1%~4%), the secreted polysaccharides such as alginate will gradually decrease, which is unfavorable to the stability of ABGS [52]. Therefore, the salinity conditions for ABGS operation need to be determined according to the salt tolerance of algae and bacteria. In open ponds, evaporation loss and rainfall are the main causes of changes in medium salinity, and the salinity level can be controlled by adding fresh water or salt to the medium.

Table 1. Regulation of key factors in microalgae treatment of aquaulture wastewater.

Influencing Factors	Parameters	Removal rate (%)	References
Light intensity	12W/m2; VSS/SS=1.3	COD: up to 100%; NH4+-N:99.6%; TP: ~100%	Qiao, S et al.,2020;
Photoperiod	12L:12D	NH4+-N: 70-95%; TP:60-85%	Li S, et al.2024; Monzón Martínez L et al., 2025;
pH	7.0–9.0	TP>60% (typically 60-80%)	Sakarika & Kornaros, Xinzhen, W et al., 2024
Hydraulic Retention Time (HRT)	18 h	COD>90%; NH4+-N> 90%; TP> 60%	Wang Xinzhen et al.
Pollutant Concentration (OTC)	OTC < 0.1 mg/L	COD>90%; NH4+-N>90%; TP>60%	Wang Y, et al. 2022; Almomani F, Örmeci B et al., 2016
Salinity	1%-4%	COD: 40-75%; NH4+-N: 5-80%; TP: 45-70% (declines with increasing salinity)	Meng et al., 2020; Tan et al., 2023

4. MICROALGAE TECHNOLOGY SYSTEM FOR AQUACULTURE

4.1 Screening and Optimization of Core Algal Strains

In the algal-bacterial granular sludge (ABGS) system, with the gradual increase of salinity (1%~4%), the secreted polysaccharides such as alginate will gradually decrease, which is unfavorable to the stability of ABGS [52]. Therefore, the salinity conditions for ABGS operation need to be determined according to the salt tolerance of algae and bacteria. In open ponds, evaporation loss and rainfall are the main causes of changes in medium salinity, and the salinity level can be controlled by adding fresh water or salt to the medium.

There are significant differences among different microalgal species in terms of growth rate, nutrient uptake preference, and environmental adaptability. Moreover, microalgae used for long-term wastewater treatment exhibit reduced activity, decreased growth rate, and lower light energy utilization efficiency. Therefore, the rational screening of microalgal species adapted to the water quality characteristics of aquaculture wastewater is the key to ensuring the efficient and stable operation of the microalgae-based treatment system.

The core of constructing a microalgae-based technology system adapted to aquaculture wastewater treatment lies in the precise screening and directional optimization of microalgal species with high pollutant removal efficiency, strong environmental adaptability, and stable biomass production. Aquaculture wastewater is characterized by complex features, including high nitrogen and phosphorus loads, large fluctuations in organic matter concentration, significant changes in salinity, and potential antibiotic residues. Therefore, ideal microalgal species must maintain high physiological activity and nutrient assimilation capacity under multiple stress conditions. Studies have shown that there are significant differences among different microalgal species in terms of growth kinetics, nutrient uptake preference, and environmental tolerance. For example, Chlorella spp. have been extensively studied due to their rapid doubling time, tolerance to high concentrations of ammonia nitrogen (some strains can tolerate more than 100 mg/L NH4+), and efficient phosphorus uptake capacity. In a comparative study of various microalgae, Chlorella vulgaris exhibited the highest biomass density in municipal wastewater and could effectively remove nitrogen and phosphorus [52]. Similarly, in aquaculture wastewater, Chlorella reinhardtii exhibits excellent purification performance, with removal efficiencies of nitrate and COD as high as 82% and 62.3%, respectively, and can completely remove TP [53]. This indicates that Chlorella is one of the preferred microalgal species for treating nitrogen- and phosphorus-rich wastewater. This indicates that Chlorella is one of the preferred microalgal species for treating nitrogen- and phosphorus-rich wastewater. Comparative studies on microalgae cultivation in domestic wastewater further confirmed that species selection is closely related to wastewater treatment efficiency and high value-added biomass production [54].

However, the directional optimization of core microalgal species is also the key to improving system performance. The optimization pathways mainly include: (1) Adaptive laboratory acclimation: By gradually increasing the proportion of aquaculture wastewater in the culture medium, 100% raw water culture is ultimately achieved, enabling the microalgal species to adapt to the stress environment of specific wastewater at the genetic and physiological levels [55]. (2) Physicochemical mutagenesis and screening: Algal cells are treated with ultraviolet (UV) radiation or chemical mutagens, and then mutant strains with enhanced tolerance are screened under the stress of high concentrations of ammonia nitrogen or specific antibiotics [56]. (3) Genetic engineering and synthetic biology modification: This is the most promising yet cutting-edge method. Through gene-editing tools such as CRISPR-Cas9, the nitrogen metabolism pathway of microalgae can be targeted and enhanced; for example, overexpressing the GS/GOGAT gene cluster, thereby significantly improving their ammonia nitrogen assimilation efficiency [55]. Furthermore, exogenous genes can also be introduced to enhance their detoxification capacity against antibiotics or heavy metals. In terms of specific microalgal species selection, it is necessary to match them according to the specific water quality characteristics of the wastewater. For high ammonia nitrogen wastewater, Nannochloropsis oceanica has attracted much attention due to its excellent ammonia toxicity tolerance [58]. For marine or brackish aquaculture wastewater, salt-tolerant microalgal species should be selected, such as Isochrysis galbana and Phaeodactylum tricornutum [55, 59], which can not only effectively remove nitrogen and phosphorus, but also synchronously degrade antibiotics such as florfenicol [57]. Co-cultivation strategies have also been proven to effectively improve treatment performance; for example, co-cultivating Chlorella sp. and Phaeodactylum tricornutum can utilize their different ecological niches and metabolic characteristics to enhance the comprehensive treatment capacity and stability of the system for complex pollutants [60].

Table 2. Screening and optimization of microalgae strains adapted to aquaculture wastewater.

Microalgae Species/Group	**Wastewater Type**	**TN removal (%)**	**TP removal (%)**	**Nitrogen removal (%)**	**COD removal (%)**	**References**
Chlorella vulgaris	Aquaculture wastewater	72–90	65-85	NH_4^+:70-95	55-80	Wan Mahari. et al., 2024;
Chlorella reinhardtii	Aquaculture wastewater	_	~100	NO_3^-:82%	62.3	Wang Q et al., 2022 [54]
Nannochloropsis oceanica	High ammonia nitrogen wastewater	60-85	50-75	NH_4^+：70-90%	45-70	Molla A et al.,2025
Isochrysis galbana	Aquaculture wastewater	60-85	60-80	NH_4^+：60-85	50-75	Zhang L et al.,2023

Table 2. (continued) Screening and optimization of microalgae strains adapted to aquaculture wastewater.

Microalgae Species/Group	Wastewater Type	TN removal (%)	TP removal (%)	Nitrogen removal (%)	COD removal (%)	References
Phaeodactylum tricornutum	Antibiotic-containing wastewater	60-80	55-75	NH_4^+:60-80	45-70	Zhang L et al.,2023; Molla A et al.,2025
Microalgae consortium (Chlorella + P. tricoenutum)	Complex wastewater	75-92	70-90	NH_4^+:75-95	60-85	Qian Z et al., 2022
Genetically optimized strains	Aquaculture wastewater	80-95	75-92	NH_4^+:85-98	65-90	Wang Q et al., 2022 [54]

4.2 Comparison of Mainstream Processing Technologies

In the field of aquaculture wastewater treatment, physical, chemical, and biological methods are three widely applied technical routes at present, and each type of technology differs in terms of treatment mechanism, removal efficiency, and engineering applicability.

Physical method

Physical removal utilizes the physical properties of materials to directly remove nitrogen and phosphorus compounds from wastewater. Traditional physical methods include adsorption, precipitation, and filtration. Adsorption technology separates nitrogen and phosphorus from water through high-efficiency adsorbents, such as activated carbon or zeolite; precipitation causes pollutants to stratify and settle through physical gravity; filtration technology relies on high-precision filter membranes to intercept particles and impurities [61]. New physical methods include membrane separation, electrocoagulation, etc. The core principle of membrane separation technology is to selectively separate and retain nitrogen and phosphorus pollutants in wastewater through semipermeable membranes, thereby achieving pollutant removal and water quality improvement [62]. Common membrane separation technologies mainly include ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and membrane bioreactor (MBR) technology. The physical method has the characteristics of simple operation and stable operation, but its removal efficiency for low-concentration pollutants is limited. Therefore, it is necessary to combine it with other technologies to improve the comprehensive treatment effect, and it is more used as a pretreatment or auxiliary measure in wastewater treatment.

Chemical methods

The chemical method is an important means of traditional nitrogen and phosphorus removal technologies. It mainly achieves the removal purpose by adding chemical agents to make nitrogen and phosphorus in the sewage undergo chemical reactions, converting them into insoluble precipitates or relatively stable and harmless compounds. Traditional chemical treatment methods include chemical precipitation, Fenton process, ion exchange, and catalytic oxidation [28]. For example, the electro-Fenton method combined with electro-oxidation (EC + EO) has been evaluated for removing pollutants from shrimp culture wastewater. The parameters such as current density, pH, and operation time were optimized by the response surface methodology to achieve the best treatment effect [29]. Some studies have explored the effect of chitosan as a biological coagulant for removing turbidity from aquaculture wastewater, and the parameters were optimized using the response surface methodology [30].

Bioanalysis

The biological method is a traditional treatment technology that uses microbial metabolic activities to remove nitrogen and phosphorus pollutants from wastewater. Through the biochemical reactions of microorganisms, nitrogen and phosphorus pollutants are converted into stable or harmless forms, thereby achieving pollutant removal [28]. Common biological treatment technologies include activated sludge process, biofilm process, sequencing batch reactor (SBR), and anaerobic-anoxic-aerobic (A2/O) processes, etc. Among them, the activated sludge process relies on suspended microbial communities to achieve the removal of organic matter and nitrogen-phosphorus; the biofilm process enhances the operational stability of the system by forming biofilms through microorganisms attaching to the surface of fillers; the SBR process strengthens the control of the reaction process through intermittent operation; and the A^2/O process achieves the synergistic removal of nitrogen and phosphorus through the setting of different functional zones [31][32][33].

The biological method has the advantages of relatively low operation cost, stable treatment effect and environmental friendliness, but it is relatively sensitive to operating conditions and changes in water quality. In practical wastewater treatment, it is often coupled with physical or chemical methods to improve the overall treatment efficiency of the system.

4.3 Coupling Technology Innovation

All wastewater treatment technologies have certain applicable scenarios in aquaculture wastewater treatment, but a single technology is difficult to balance treatment efficiency, economy and sustainability. The reasonable coupling of microalgae biological treatment technology with physical or chemical methods is an important development direction for improving the treatment effect of aquaculture tail water in the future. For example, integrating activated sludge and microalgae processes can maintain wastewater treatment performance while reducing greenhouse gas emissions, indicating that microalgae-based coupling systems have potential advantages in both pollution control and carbon reduction [75].

A large number of studies have been carried out on the compound microbial community treatment technology and electrochemical-related coupling processes in terms of nitrogen and phosphorus removal and resource utilization. Existing studies have shown that the synergistic removal efficiency of nitrogen and phosphorus in wastewater can be effectively improved, and the operational stability of the system under low-temperature and low-nutrient conditions can be enhanced by using functional microbial communities such as composite nitrifying bacteria, denitrifying bacteria, and phosphorus-accumulating bacteria. Abdalla Hcombined the bioelectrochemical system with the MAP crystallization process [62]. In the Microbial Fuel Cell (MFC), the OH^- generated by the cathodic reaction was used to increase the local pH, realizing the synergistic enhancement of the simultaneous recovery of nitrogen and phosphorus in wastewater and the electricity generation process. Zhou et al. studied the electrochemical denitrification process of nitrate pollution in water bodies [63]. With the assistance of electrochlorination, ammonia can be efficiently oxidized to N_2, with the N_2 selectivity reaching 96.81%. Song et al. integrated manganese ore and activated carbon particles into the constructed wetland microbial fuel cell system [64]. Under the condition of COD/N ratio of 1.7, the removal efficiency of influent total nitrogen was 53.5% higher than that of the control system. Yuan et al. developed an iron phosphide nanoarray electrocatalyst for the efficient reduction of nitrite in wastewater to ammonia, with a Faraday efficiency of 82.5% ± 2.3% [65]. Kong et al. used nano zero-valent iron supported by biochar to remove nitrate in the cathode of bioelectrochemical system, and completely removed NO-N [66] within 28 hours. Zulkifli et al. reviewed the research progress of ammonia nitrogen removal by biofilm reactor, and the highest removal rate reached 99.7% [67]. Petta et al. evaluated the treatment effect of real brewery wastewater through a multistage pilot system, and the removal rate of total nitrogen reached 67% [68].

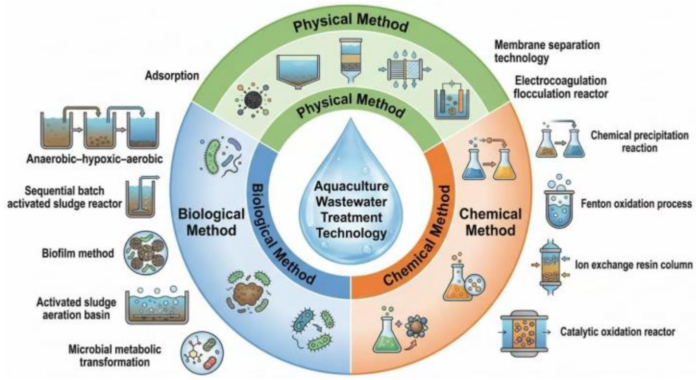

Figure 1. Classification of Aquaculture Wastewater Treatment Technologies and Schematic Overview of Microalgae-Based Bioremediation.

5. EXISTING BOTTLENECKS AND RESTRAINING FACTORS

Although microalgae and algae-bacteria symbiotic systems have shown good pollutant removal effects in aquaculture wastewater treatment, they are currently restricted by two factors: technology and economy.

At the technical level, this system is very sensitive to changes in environmental conditions such as light, temperature, and water quality. The aquaculture wastewater has large fluctuations in water quality and complex pollutant components, which are likely to inhibit the activity of microalgae, disrupt the symbiotic relationship between algae and bacteria, and thus affect the removal efficiency of nitrogen and phosphorus. At the same time, long-term continuous operation will also lead to problems such as decreased algal activity and changes in biological communities. Moreover, for micro-pollutants such as refractory organic compounds and antibiotic residues in wastewater, the removal effect of the microalgae system is not ideal, making it difficult to ensure the treatment effect and operational stability when treating water quality on a large scale.

At the economic level, although the microalgae treatment technology reduces the input of a large number of chemical reagents and the cost of treating secondary pollution, the initial equipment investment during the construction phase of the microalgae system is relatively high, including reactors, supporting lighting, stirring, monitoring and other related equipment. Currently, the resource utilization of microalgal biomass is not yet mature. The market value and conversion efficiency of related biomass products are uncertain, making it impossible to reduce the treatment cost through resource recovery, which further reduces the economic feasibility of this technology.

6. FUTURE DEVELOPMENT DIRECTION

6.1 Technical Precision Optimization

Focusing on the technical bottlenecks of microalgae and algae-bacteria symbiotic systems in aquaculture wastewater treatment-such as weak environmental adaptability, insufficient system stability, and limited removal effect on refractory pollutants-future research should focus on precise technical optimization. By means of targeted screening, long-term acclimation combined with genetic engineering methods, the tolerance of strains to high ammonia nitrogen and high salinity as well as the nitrogen and phosphorus assimilation efficiency can be improved [28]; alternatively, engineered fungi-microalgae combinations can be bred, or non-pathogenic fungi can be screened to construct symbiotic systems, so as to enhance the adaptability of the system to complex wastewater environments [70]. By means of targeted screening, long-term acclimation combined with genetic engineering methods, the tolerance of strains to high ammonia nitrogen and high salinity as well as the nitrogen and phosphorus assimilation efficiency can be improved [28]; alternatively, engineered fungi-microalgae combinations can be bred, or non-pathogenic fungi can be screened to construct symbiotic systems, so as to enhance the adaptability of the system to complex wastewater environments [70].

6.2 Resource Utilization and High-Value Upgrading

The resource-oriented and high-value utilization of microalgae and algae-bacteria symbiotic systems is an important direction to improve the economic efficiency of this technology and promote its practical application. While treating aquaculture wastewater, this system can harvest microalgal biomass to achieve the resource recovery of sewage [70]; through the development of conversion technologies, these biomass can be processed into high-value products such as biofuels, bioplastics, and biodiesel, and can also be made into practical products such as animal feed and fertilizers [28] [69]. In the downstream stage, electrochemical harvesting, industrial harvesting and bioflocculant-assisted harvesting can improve the recovery efficiency of algal biomass and support its further conversion into biofuels and other high-value products [71] [72] [73]. In addition, algae can also extract pigments, antioxidants, etc., to further enrich the utilization approaches. Meanwhile, cultivation and harvesting technologies should be evaluated together with environmental sustainability and life-cycle assessment to improve the practical feasibility of microalgae-based treatment systems [74]. At the same time, this system also has the characteristics of energy conservation and carbon reduction. Microalgae fix carbon through photosynthesis, which does not require additional aeration for oxygen supply and will not emit CO_2. While treating wastewater, it is consistent with the demand for green development [70].

7. CONCLUSION

As a green water treatment technology based on the metabolic processes of photosynthetic microorganisms, microalgal technology has attracted extensive attention in the field of aquaculture wastewater treatment in recent years, and has gradually advanced from the basic research stage to engineering application. Microalgae absorb nitrogen, phosphorus and other nutrients from water bodies through photosynthesis and convert them into cellular biomass, thereby achieving efficient pollutant removal. Meanwhile, in practical systems, microalgae often form a stable algae-bacteria interaction relationship with bacteria, which further enhances the system's synergistic removal capacity for composite pollutants such as organic contaminants, antibiotics and heavy metals through mechanisms such as material exchange, metabolic complementarity and signal regulation.

Studies have shown that the pollutant removal efficiency of microalgal treatment systems is largely affected by environmental factors including light intensity, pH and salinity. In the meantime, the optimization of process parameters such as hydraulic retention time and nutrient load also plays a crucial role in the stable operation of the systems. In addition, the design and application of various photobioreactors have provided key support for the large-scale operation of microalgal technology, continuously boosting its application potential in practical water treatment engineering.

Currently, the research focus is gradually shifting from the removal of a single pollutant to the resource utilization of pollutants. By converting inorganic nutrient elements in wastewater into high-value-added microalgal biomass and its metabolites, the coordinated development of pollution control and resource recovery is realized. This trend provides a new research direction for microalgal technology to achieve the green development model of “treatment-reuse-valorization” in aquaculture wastewater treatment.

In the future, it is necessary to further strengthen research on microalgal metabolic mechanisms and algae-bacteria interaction relationships, improve the adaptability of systems to environmental fluctuations, and combine cutting-edge technologies such as synthetic biology and artificial intelligence to drive the development of microalgal treatment systems toward high efficiency, intellectualization and sustainability, thus providing more reliable technical support for the green treatment and resource utilization of aquaculture tailwater.

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