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Applications of Microalgae-Based Technology in Environmental Engineering

Yaqi Li, He Huang*

College of Chemical and Environmental Engineering, Yangtze University, Jingzhou Hubei, 434023, China

Abstract

This article outlines the current applications of microalgae-based technology in the three major areas of environmental engineering, which are wastewater treatment, greenhouse gas emission reduction and biomass energy. Briefly explains the mechanism of microalgae removal of pollutants and the current problems. In addition, the view that the three directions could be combined in the future research is pointed out, so as to provide a basis for microalgae to play its greatest role in the field of environment.

Keywords: Microalgae; Wastewater Treatment; Greenhouse Gas Emission Reduction; Biomass Energy.

1. Introduction

With the development of economy, the types of pollutants in water environment become more and more complex. For example, the concentrations of antibiotics, polybrominated biphenyls, polycyclic aromatic hydrocarbons, bisphenols, organochlorines, pesticides, and heavy metals in water are increasing year by year. This will pose a certain threat to the water environment. However, microalgae can absorb, enrich and metabolize these pollutants in the environment, and convert them into carbon, nitrogen and sulfur sources needed for their own develop and multiplication. In recent years, the use of microalgae to remove refractory organic compounds in sewage have been studied. Also, heavy metal, which caused pollution have become a global problem, especially in developing countries, which is algae growth cannot lake of. And a lot of wastewater after processing, such as aquaculture wastewater, still remain a lot of N, P nutrition elements, if not clean it correctly, it will cause eutrophication of nearby rivers and lakes, but these are exactly what algae need to grow.

As we all known, microalgae are typical autotrophic organisms in nature. They can use carbon dioxide in the air and nitrogen, phosphorus and other nutrient elements in the water through photosynthesis to achieve their own growth and reproduction purposes. At the same time, they can produce oil, sugar and other biomass energy. Based on this, wastewaters provide a good habitat and nutrient sources for them, and flue gas gives them carbon dioxide to breathe. Therefore, using microalgae-based technology as a bioremediation means to alleviate environmental and energy pressures is a green, economic and sustainable method.

2. Application and mechanism of microalgae in wastewater treatment

2.1 Remove refractory organic matter from wastewater

We should focus on antibiotics, especially in this year. The widespread use of antibiotics has potential harm to aquatic ecology, and traditional sewage treatment methods cannot effectively remove them. A large number of studies have shown that most antibiotics have a direct effect on algae, which may not only inhibit the growth of it as a toxin, but also produce toxic stimulation effect at a specific concentration, further activate protease, regulate synthesis and induce gene expression, so as to promote the growth of microalgae cells. The toxic effect of antibiotics on microalgae presents "low concentration promotes while high inhibition" [1,2,3,4]. This phenomenon indicates that within a certain concentration, algae can absorb and enrich antibiotics and degrade them to achieve the purpose of removing antibiotics from sewage. However, the types and concentrations of antibiotics in sewage will have a great impact on the treatment results. And the sensitivity of the same microalgae to different kinds of antibiotics is different. For example, Ling [5] have studied the toxicity of 13 kinds of antibiotics on *Pseudokirchneriella subcapitata*. The result shows that protein-synthetic antibiotics, such as azithromycin, doxycycline, fluorine benzene nicol, etc, have obvious toxic effects on algae. But cell walls synthesize inhibitory antibiotics, such as cefotaxime sodium, amoxicillin, etc, have almost nontoxic to algae. According to the classification of antibiotics, macrolides and tetracycline antibiotics have obvious toxic effect, where β-lactamides antibiotics are un-conspicuous. This conjecture is consistent with the conclusion drawn by Wang [6]. In the same way, the study of the toxicity of the same antibiotics to different microalgae have been done much. For instance, Qian et al [4], have studied the effects of streptomycin on *Chlorella vulgaris* and *Microcystis aeruginosa*, the result shows when expose to the same medicine, EC_{50} of *Microcystis aeruginosa* is 0.28 mg/L, where *Chlorella vulgaris* is 20.08 mg/L. Thus, it is necessary to choose a kind of algae, which can tolerant high concentration of antibiotics while removing them.

Most of the current studies focus on toxicity, but lack of researching microalgae used to treat antibiotics containing wastewater. However, we shouldn't ignore it. The efficiency of *Nannochloropsis oculate* and *Pseudokirchneriella subcapitata* is 57.0% and 51.25%, when aiming to remove norfloxacin in the concentration of 20μg/L after 144h and 120h, respectively, in the study of Chen et al [7]. And this study also points out that the removal rate of sulfadiazine is 78.3% at an initial concentration of 20μg /L with 144h exposure times. Kassandra et al [8] compared the removal of ciprofloxacin at 25μg/L with and without *Scenedesmus dimorphus*, the efficiency is 93% and 53%, respectively. A precious article, which is from Claude kiki [9], have investigated *Haematococcus pluvialis*, *Selenastrum capricornutum*, *Scenedesmus quadricauda*, and *Chlorella vulgaris* used for removing four kinds of sulfonamides, three kinds of fluoroquinolones, and three kinds of macrolides antibiotics. The results show that *Haematococcus pluvialis* is the most widely applicable for it's removing efficiency is over 50% for all antibiotics, and is a considerable algae to sort out sulfamerazine, sulfamethoxazole, sulfamonomethoxine, and lomefloxacin. On the contrary, if the removal substance is not lomefloxacin, *Scenedesmus quadricauda* would be a bad choose. Song et al [10,11] have found that *Chlorella sp.*L38和*Chlorella sp.* UTEX1602 have a good efficiency of removing two kinds of veterinary antibiotics, florfenicol and thiamphenicol.

From the above studies, it can be found that algae have a certain effect on the removal of antibiotics, or in other words, have a certain promoting effect. Different algae have different effects on the removal of the same antibiotics and vice versa. Therefore, the relationship between the existing algae with good treatment effect and the corresponding antibiotics species could be classified. The dominant algae in local water can be domesticated or modified with genetic engineering technology, so as to obtain more adaptable and more effective algae species.

If the low concentration of antibiotics can provide carbon source and inhibit the growth of bacteria to have certain benefits to microalgae, the toxic pollutants such as polybrominated bisphenols, bisphenols and pesticides are completely harmful to algae. However, microalgae still can remove these toxic organic pollutants (Table 1).

Table 1: Degradation of toxic organics by different microalgae

Type of algae	**Time(d)**	**Pollutant**	**Initial concentration**	**remove rate (%)**	**References**
Chlorella SICH	7	polybrominated diphenyl ethers	60-600μg/L	82-90	[12]
Cyclotella caspia	16	bisphenol A	8mg/L	36.44	[13]
Chlamydomonas mexicana	10	carbamazepine	1mg/L	35	[14]
Scenedesmus obliquus	10		1mg/L	28	
algae system	8	pesticides	10μg/L	99	[15]
Arthrospira maxima and *Chlorella vulgaris*	6	4-nonylphenol	9.29mg/L	98.3	[16]

Algae may have the same mechanism of removing toxic substances as bacteria, which first adsorb organic matter on its surface through adsorption, and then degrade pollutants through bio-enrichment, co-metabolism, and induction of corresponding enzyme system. At present, algae treatment of refractory organic matter and its degradation mechanism need to be further studied.

2.2 Remove inorganic pollutants from wastewater

There are a lot of scholars have studied the use of algae to deal with the residual N and P nutrient elements in the water, and achieved good effect. Most studies have shown that *Chlorella sp.* and *Phyllorella sp.* are two kinds of algae that have the best treatment effect on N and P, meanwhile have the best tolerance to high ammonia nitrogen and can also produce oil well [17]. The types of wastewater include domestic sewage, landfill leachate, aquaculture wastewater tail water, industrial wastewater, etc. (Table 2). The forms of algae utilization mainly include: direct use, as cathode material for microbial fuel cells [18], algal-bacteria symbiotic system [19], and microalgal biofiltration membrane [20]. Among them, the creation of algal-bacteria symbiotic system, that is, algal-bacteria co-culture to remove pollutants in wastewater is a major research focus at present. According to researches, algal-bacteria co-culture method can significantly improve the biomass of algae and the removal rate of COD and P [21,22,23]. The reason is that when microalgae and bacteria exist together, the degradation of pollutants shows a synergistic effect. Like activated sludge, algae can suspend and immobilize in sewage [24], these two kinds of existence state have their own advantages and disadvantages. When considering oil yield, the immobilized body algae is not as good as that of the suspended system, and the immobilized materials may affect the gas transfer and photosynthesis of algae. Selection and preparation of immobilized materials is also a big problem. However, it is difficult to harvest algae from the sewage, which may affect the water quality of the effluent and lead to unstable treatment effect due to the easy loss of dominant bacteria [25].

There is pilot test of using algae remove nutrients in the wastewater [22], studies have shown that algae can grow healthily in the wastewater which is containing bacteria and it can like activated sludge to be domesticated. In future research, we can consider to treat wastewater, especially aquaculture wastewater, not after sterilization steps, just through training the algae, make it can adapt to the natural conditions of sewage, probably for industrial use.

The process of microalgae removing inorganic matter is generally autotrophic metabolism, and the removal efficiency of N and P is determined by the N/P ratio. The N/P ratio varies from 8 to 45 g with different species of microalgae [26,27]. Some scholars have studied the mechanism of microalgae to absorb inorganic nitrogen, which is under the specific enzymes assist, microalgae absorbed nitrate, nitrite and ammonia nitrogen into cells directly at first, and then, with the help of specific enzymes and ATP, algae reduce nitrates and nitrites into amines and incorporate then into the carbon skeleton [28]. Microalgae use carbon dioxide as carbon source with the step of photosynthesis will reduce the content of CO_2 in sewage, increase the pH, and increase the volatilization of ammonia nitrogen. Under the condition of high pH, phosphate combines with calcium ions in water to form calcium phosphate precipitation, thus achieving effective denitrification and dephosphorization [25].

It is a good choice to use microalgae to treat N and P nutrient elements and COD and other inorganic substances in various types of wastewater. However, at present, it can only be used in laboratory or pilot test, and there are still many problems to be solved in industrial application. Therefore, the emphasis of future research should be placed on: (1) improve the separation efficiency of microalgae and sewage, increase the follow-up treatment and utilization rate of microalgae, and increase the economic value of using microalgae to treat sewage; (2) direct separation of dominant algae species from local sewage and put them into use; (3) when immobilized algal bacteria symbiosis system is considered, embedding materials with low price, non-toxic, good light and air permeability and hard to be degraded should be thought.

Table 2: Removal of N and P nutrient elements by different microalgae

Type of algae	Type of sewage	Time (d)	Removal rate (%)			Oil production rate	References
			TN	TP	COD		
Chlorella zofingiensis	swine wastewater	10	82.7	100	79.8	110.56mg/L·d	[29]
Chlorella pyrenoidosa	mixed wastewater	9	91.6	90.7	75.8	127.71 mg/L·d	[30]
Chlorella vulgaris	Simulated wastewater	10	88.9	80.3	86.6	--	[19]
Chlorella vulgaris	Biogas slurry	48	98.1	100	--	--	[31]
Chlorella vulgaris	sewage	14	79.6	79.6	--	36% of the dry weight	[32]

The problem of heavy metal pollution in water bodies also should be concerned. Some metal ions, though, algae cannot directly used but can remove them by adsorption. At present, the adsorption of copper, zinc, lead, cadmium, chromium (Cr^{3+} and Cr^{6+}), cobalt, mercury and other heavy metal ions by microalgae has been studied [33,34]. When it is used to remove heavy metals in sewage, there are two forms of utilization: living alga and inactive alga, among which the inactive alga is more efficient in removing heavy metals [33]. The results showed that there are two types of adsorption of heavy metals by living algae: (1) one or more of the following ways, which are coordination, complexation, ion exchange, physical exchange and microprecipitation, that are not related to the physiological activities of algae are only related to the cell structure and surface groups of algae at this condition [35,36,37]; (2) biosorption, a process associated with algae metabolism in which metal ions are stored in the algae [38,39,40,41].

At present, there have been extensive studies on the removal of heavy metals from water by microalgae at home and abroad, and some research have good achievements. However, the large-scale popularization and application of microalgae are always a major difficulty in algae utilization. In the future, more attention should be paid to the screening and domestication of algae species with high tolerance, or deepen the mechanism research, in order to break through from the mechanism of algae to heavy metal adsorption performance.

3. Application of microalgae in atmospheric

Because of their high photosynthetic efficiency, fast growth rate and strong stress resistance [42], microalgae carbon sequestration technology has become a promising new technology for reducing greenhouse gas emissions. The current research mainly focuses on: (1) screening of efficient carbon sequestration algae and optimizing the culture conditions; (2) gene regulation changes the carbon sequestration and carbon tolerance of algae; (3) development of high efficiency photobioreactor; (4) mechanistic studies.

At present, the main problems of photosynthetic carbon sequestration in microalgae are as follows: (1) application difficulties. Illumination in the laboratory is controllable, but in the natural environment is not. Lack of theoretical research on CO_2 absorption process, unable to provide design data for industrial production process, difficult to meet the requirements of quantitative control, economic and site constraints; (2) research difficulties. At present, the known carbon sequestration process of microalgae is: transfer CO_2 from the gas phase to the liquid phase; Transfer CO_2 from liquid phase to algal cells; algal cells convert CO_2 into the stuff they need to grow. The first two processes are related to fluid flow and mass transfer equipment, which are physical processes, and the last is a biological transformation process. At present, the influence of CO_2 concentration, temperature, pH and light on carbon sequestration rate has been studied in the optimization of culture conditions, which is a macroscopic study. However, due to the uncertainty of mass transfer process, the subsequent results are uncertain and difficult to repeat, and the research results will be biased accordingly. So, the research methods should be improved to make them more scientific and accurate; (3) The design of photobioreactor is difficult. Application of additional products should be further studied [43,44].

4. The application of microalgae in new energy direction

In the past five years, there were studies on the combination of oil production and wastewater treatment or CO_2 emission reduction of microalgae, among which wastewater treatment and oil production were the most studied, followed by CO_2 emission reduction and oil production, and finally, the combination of wastewater treatment and oil production. There is almost no combination of all three. The reason may be that it is simple to make the two aspects achieve the best effect, but it is difficult to balance the three. Microalgae must grow without water, but CO_2 is not necessary by comparison. So, the focus is different, but each study has its own significance.

5. Conclusions

Since the three aspects of wastewater treatment, CO_2 emission reduction and oil production are related to algae and independent of each other, the three can be combined in future research to achieve an optimal balance. The optimal application conditions and optimization techniques (preferably adapted to climate change) should be selected after comprehensive consideration: hydraulic residence time, algal body existence form, temperature, selection and preparation of embedded materials, genetic engineering regulation, etc. There are also many difficulties to be solved in the utilization of algae:

1. Due to the lack of thorough research on the mechanism, the results are still difficult to be repeated under laboratory conditions, resulting in the difficulty in expansion and providing a theoretical basis for practical application;
2. The separation technology is not mature enough, and it is difficult to separate the wastewater and microalgae after treatment, resulting in a large number of algae lost and treatment is not very efficiency. In addition, microalgae are limited enrichment and removal ability of pollutants in the wastewater, so it cannot completely purify the wastewater;
3. Due to the difference between the natural environment and the laboratory environment, microalgae can achieve some results in the laboratory, but cannot in the natural environment;
4. The facilities required for algae use cover a large area.

In the future, when used in the field of environmental engineering, we should consider more, such as optimize the condition to the highest oil yield, and combined the knowledge of materials engineering, chemical engineering, manufacturing, biotechnology engineering and related disciplines to create a structure, which is simple, high value transfer rate of the runway pool or light bioreactor, this will be the applications of microalgae a stride.

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