Trends and progress in Microalgae-based wastewater treatment technologies: A review

Yujia Wan[1, †], Ning Yan[2, †], Jiaqi Zhao[2, †] and Hegang Zhi[3, †], Wenmin Wang[4, *]

[1]*Faculty of Resources and Environmental Science, Hubei University, Wuhan 430062, China*
[2]*College of Environment, Hohai University, Nanjing 210098, China*
[3]*College of Agricultural and Environmental Sciences, University of California, Davis 95616, United States*
[4]*Shenzhen International Graduate School, Tsinghua University, Shenzhen 518055, PR China.*
[†]*These authors contributed equally.*

Abstract. A transformative change is underway in wastewater treatment as the world aims at meeting Sustainable Development Goal 6 in 2030, and the conventional wastewater treatment processes have high energy consumption and greenhouse emissions. Microalgae-based wastewater treatment process has emerged as an innovative technology that can reach the demand for lowering energy consumption, mitigating climate change, and recycling resources. This review provides an overview of the basic theories of microalgae-based wastewater treatment processes, microalgae species commonly used, impact factors of microalgae cultivation, the conventional and hybrid microalgae-based wastewater treatment systems. Moreover, suggestions are proposed for further research and development.

Keywords: Microalgae cultivation; Wastewater treatment; Nutrient removal; Biomass production.

1. Introduction

According to the 2030 Agenda for Sustainable Development (SD), the SD Goal (SDG) 6 aims at ensuring availability and sustainable management of water and sanitation for all. However, the study shows that we are still far from this goal. Two-thirds of the world's population currently lives in areas that experience water scarcity for at least one month a year [1]. The significant reasons for water scarcity are contamination of water resources, the low proportion of wastewater treatment, and the lack of technologies to reclaim the used water. In fact, nearly 1,000 km^3 of wastewater is generated around the world and Over 80% of the world's wastewater is released into the environment without treatment; for municipal wastewater in China, only 16.6% of municipal wastewater is reused and the recovery rates of organics, NH_4-N and TP are less than 40% [2]. To address these issues, stringent rules have been released to limit the discharge of pollutants, increase wastewater treatment rates and enhance resource recycling in many countries. However, the most widely used wastewater treatment processes are facing the challenges of nutrient removal and recovery to meet the requirements of discharge and wastewater reuse and promote a circular economy.

For the past century, a bulk of wastewater has been treated by conventional wastewater treatment processes (Fig.1), such as anaerobic treatment process, aerobic activated sludge treatment process, nitrification-denitrification, chemical phosphorus removal, and secondary sedimentation, having difficulties in meeting the more stringent discharge standards and the needs of recycling resources. In addition, conventional wastewater treatment processes could account for up to 3% of global electricity and nearly 1.57% of global GHG emissions (49 Gt CO_2e) in 2010 [3], hindering wastewater treatment from sustainable development.

Microalgae-based wastewater treatment (MBWT) processes (Fig.1) were studied as wastewater treatment and nutrient recovery technology first in 1950' by Oswald and Gotaas [4]. In these decades, many researchers have found the potential benefits of the typical MBWT process comparing to conventional process (Fig.1) as (1) lower cost of wastewater treatment; (2) biological denitrification and phosphorus removal simultaneously and more efficiently with lower sludge generation; (3) the ability to function as carbon capture and utilization (CCU) technology; (4) the generation of biomass which can be

*Corresponding author: wangwm17@mails.jlu.edu.cn (Wenmin Wang)

used to produce fertilizer, biogas, biofuel, and energy. However, the conventional MBWT processes, such as open ponds, have some drawbacks, such as the low biomass productivity and high cost for harvesting, which could be addressed by developing a microalgae-based hybrid system.

Therefore, this review introduces the basic theories and impact factors of the MBWT process and focuses on the trends and progress of the MBWT process, and analyzes the issues that need to be overcome in future research and development.

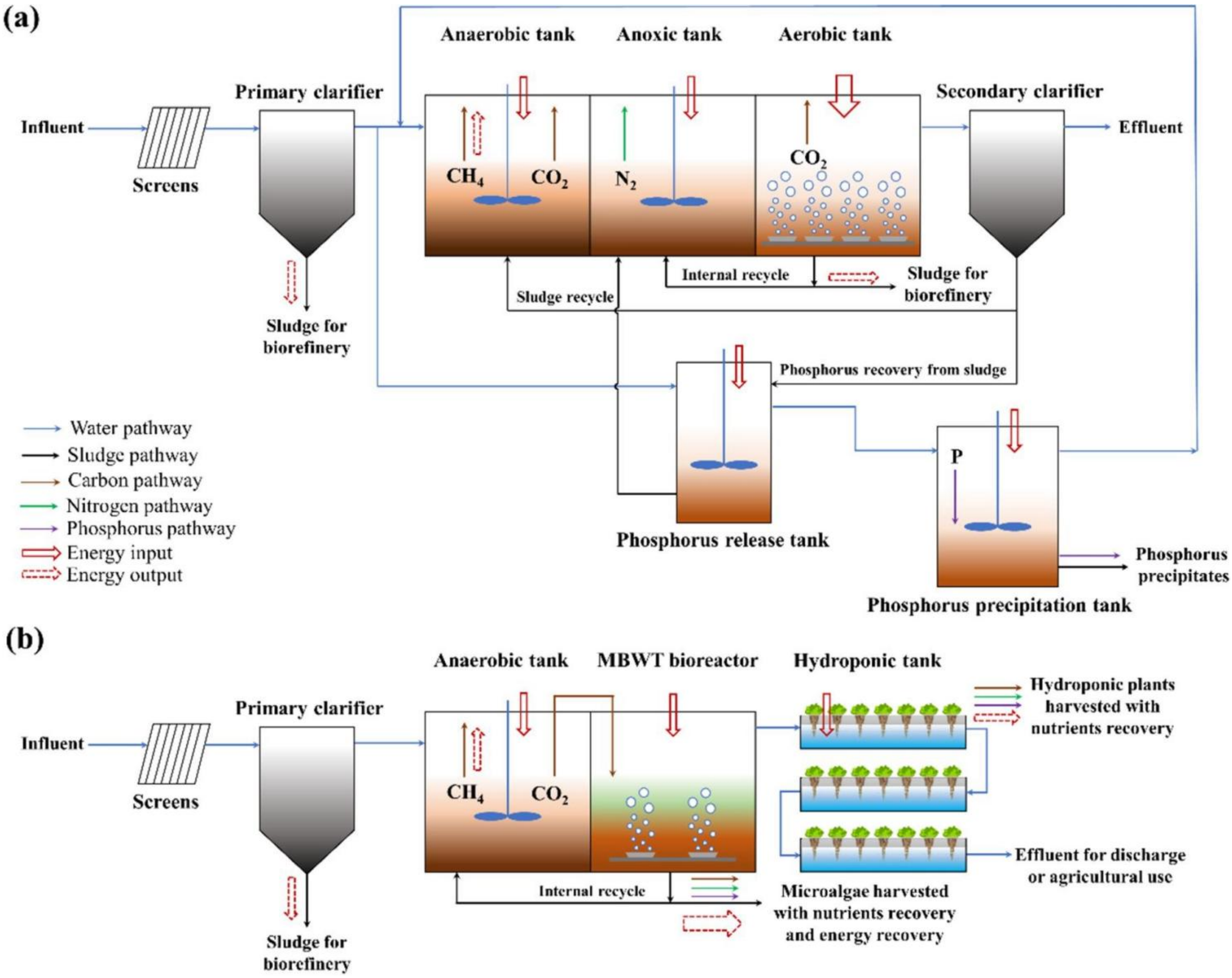

Figure 1. Comparison between nutrients recovery enhanced conventional wastewater treatment process (a) and typical MBWT process (b) [5].

2. The basic theories and factors of MBWT

2.1 The mechanisms of nutrient removal in wastewater by microalgae

Microalgae uptake nutrients in wastewater as it grows, and it is removed and recycled in further treatment to achieve nutrient removal and recovery. Generally, carbon is the basic element of organics that need to be removed, and nitrogen and phosphorus removal are most considered since they can lead to eutrophication. In recent years, carbon removal in the atmosphere is also highly valued as a way to mitigate climate change.

2.1.1 Carbon removal

The carbon source is an indispensable part of the growth of microalgae, and it can be acquired from the atmosphere and wastewater. Carbon dioxide dissolved in the water enters the cell in the form of free diffusion and is fixed through the photosynthetic activity of autotrophic microalgae. Soluble carbonates can be utilized by direct uptake or conversion of carbonate to free carbon dioxide through carbohydrase activity. Some microalgae have heterotrophic behavior, using organic forms of carbon such as glucose, sucrose, ethanol, and so forth [6].

2.1.2 Nitrogen removal

Microalgae play a key role in converting inorganic nitrogen to its organic form through a process called assimilation. As shown in Fig.2, translocation of the inorganic nitrogen occurs across the plasma membrane, followed by the reduction of oxidized nitrogen and the incorporation of ammonium into amino acids. Ammonium is thought to be the preferred form of nitrogen because a redox reaction is not involved in its assimilation; thus, it requires less energy. Studies have shown that, in general, algae tend to prefer ammonium over nitrate, and nitrate consumption does not occur until the ammonium is almost completely consumed.

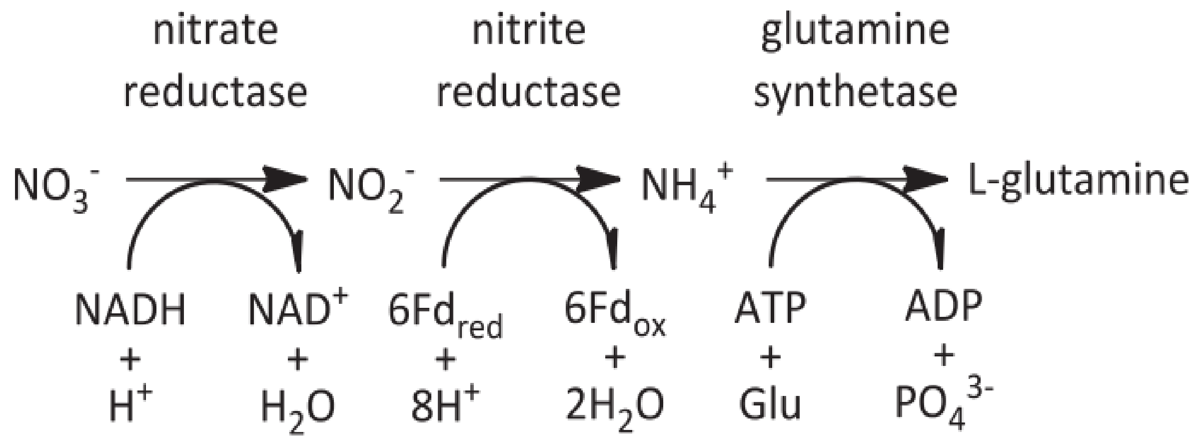

Figure 2. Simplified schematic of the assimilation of inorganic nitrogen [7].

2.1.3 Phosphorus removal

Phosphorus is also a key factor in the energy metabolism of algae. During algae metabolism, phosphorus, preferably in the forms of $H_2PO_4^-$ and HPO_4^{2-}, is incorporated into organic compounds through phosphorylation, much of which involves the generation of Adenosine Triphosphate (ATP) from adenosine diphosphate (ADP), accompanied by a form of energy input.

2.2 Screening of microalgae species used in wastewater treatment

The growing of different microalgae species and strains have different requirements for nutrients and lighting and have great differences in environmental adaptability in growth rate, yield, and so forth. Not all of the microalgae species are qualified for wastewater treatment. Therefore, it is necessary to screen and domesticate microalgae species according to the characteristics of different wastewater. After decades of studies, researchers have formed criteria for microalgae species used in wastewater treatment, including (1) fast growth rate; (2) high nutrient removal rate; (3) high biomass productivity; (4) strong adaptability to a different type of sewage and local climate. When criteria cannot be met at once, “fast growth rate” should be the priority.

A great number of microalgae species have been applied to wastewater treatment. One commonly used microalgae species in *Chlorella* sp. [8-10], including C. *kessleri*, C. *pyrenoidosa*, C. *sorokiniana*, C. *vulgaris*, C. *reinhardtii*, C. *emersonii*, and so forth. There are other species, such as *Scenedesmus* sp. (S. *dimorphus*, S.*obliquus*), *Arthrospira* sp. (A. *platensis*), *Spirulina* sp. (S. *maxima*), *Botryococcus* sp. (B. *braunii*), *Phormidium* sp. (P. *bohneri*, P. *laminosum*), *Chlamydomonas* sp. (C. *reinhardtii*), also been widely used in wastewater treatment. In addition, separating and using dominant microalgae strains from local waste streams might have a higher growth rate and nutrient removal rate [11].

2.3 Different wastewater treated by microalgae and its performance

Different waste streams have different nutrient compositions and ratios. Municipal wastewater and agricultural wastewater are appropriate to treat by MBWT since these waste streams have moderate pH and contain more nutrients that can be absorbed in algae growth, such as nitrogen and phosphorus, which is suitable for microalgae breeding. Other wastewater such as food processing effluents from milk, beer, beverage, and vegetable oil processing plants can also be treated with MBWT. Compared with them, industrial wastewater has deficient nutrients, a higher concentration of pollutants, and extreme pH conditions, which makes it difficult for microalgae growing. However, there are still some conditions of industrial wastewater suitable for microalgae treatment, with low pH and a large amount of sulfate. Study shows the removal rates of nitrogen, phosphorus, and chemical oxygen demand (COD) can reach nearly 100%, and sulfate removal rate can also reach 46% [12].

The nutrient removal and biomass production rate are pretty high by MBWT. For example, C. *reinhardtii* cultured in municipal wastewater could consume almost 100% nutrients from wastewater, with biomass of 2.0g/(L·d) and oil content of 25.25% (w/w) [13]. C. vulgaris cultivated in pig manure wastewater can produce fatty acids 0.23 g/(m^2·d) together with

Table 1. The performance of different microalgae species in certain wastewater environment

Wastewater type	Microalgae Genus and species	Removal time	Removal rate (%) COD	TN	TP	Biomass productivity	Ref.
Municipal wastewater	*Chl. vulgaris*	2-10d	-	55-88	12-100	-	[15]
	S. obliquus	0.2-8d	-	79-100[a]	47-98	-	[16]
	Oscillatoria sp.	14d	-	100	100	-	[17]
	P. tricornutum	14d	-	80-100	50-100	-	[18]
	Fil. Blue-green algae	8d	98	100[a]	54.5-72.6	10.9 g / (m2·d)	[19]
Industrial wastewater	*Chl. pyrenoidosa*	5d	-	87-89	70	0.64 g / (L· d)	[20]
	Chl. vulgaris	5-9d	-	30-95[a]	20-55	-	[21]
	S. diomorphus	9d	-	-	20-55	-	[21]
	Ar. platensis	15d	-	96-100[a]	87-99[b]	-	[22]

efficient removal of nutrients [14]. Generally, different microalgae species have significant differences in nutrient removal. The performances of different microalgae species under corresponding waste streams are listed on Tab.1.

2.4 Factors affecting the performance of microalgae and improvements

It is proved that there are many factors that can affect the nutrients removal and biomass production rate, including light, nutrient ratio (C/N and N/P ratios), pH, temperature, CO_2 concentration， Hydraulic Retention Time (HRT), cultivation mode, symbiosis, and so on [23]. Certain modifications can help microalgae withstand the changeable wastewater environments and get better performance.

2.4.1 Light

The influence of light is mainly derived from light intensity, light wavelength, and light-dark cycles. The photosynthesis process of microalgae increased with light intensity under adequate nutrients conditions till the saturation point (about 300–500 μmol photons/(m^2·s), depending on the species) [24]. Light intensity above the saturation point can cause an increase in photoprotective pigments. Therefore, changing light intensity could effectively control the composition of the microalgae system. For instance, higher intensities favored algal growth over nitrifying bacteria.

Adjusting light wavelength also has effectiveness. When cultivating *Coscinodiscus granii*, red and blue lights reach higher growth rates significantly, compared to yellow, orange, green, and white at the same intensity below the saturation point. And mixed LED light wavelength treatment (red: blue = 5:5) leads to higher Chlorella sp. growth, nutrient removal rates compared with blue, red, and white light [25].

Compared with constant light, light-dark cycles make a higher algal biomass growth rate, better biomass output, and a totally different cellular composition. The growth of bacteria improved by dark cycles enhances COD removal from wastewater. While under light cycles, it promotes N and P removal. Moreover, longer dark cycles improve the heterotrophic growth of microalgae, enhancing organic carbon removal.

2.4.2 Nutrient ratios

Nutrient ratios (C/N and N/P ratios) are crucial to the cultivation, nutrient assimilation, biomass productivity of microalgae. Generally, nutrient ratios vary significantly with the types of wastewater and need adjustments to gain a high growth rate of microalgae.

The balanced C/N ratio is significant to the nitrogen assimilation of microalgae. Ma et al. [26] investigate the nutrient removal rates and biomass productivity with a variation of the C/N ratio of molasses wastewater. The research showed that COD was better removed under the low ratios of 5 and 10, and the best lipid productivity was in a ratio of 15 with relatively good removal rates of 90.5%, 88.6%, and 87.2% for nitrogen, phosphorus, and COD, but the ratio of 20 would lead to a low growth rate of microalgae and bad performance. Besides, when the C/N ratio increased, the lipid content also increased while the biomass productivity decreased. To gain a balanced C/N ratio, one way is to mix different types of wastewater. Zheng et al. [27]successfully gained a balanced C/N ratio of 7.9 by mixing brewery wastewater in piggery wastewater, and the results showed that the removal rates could achieve 100%, 96%, 90%, and 93% for NH_4-N, TN, TP, and COD, respectively, with the productivity of 2.85g/L. Another way is to add carbon sources. Glucose, Sodium acetate, and methanol are usually function as additional carbon sources. However, in recent years, adding CO_2 through aeration or obtaining exogenous CO_2 through chemical plants nearby are considered to have more benefits in the autotrophic growth of microalgae, control of water pH, and nutrient removal.

The N/P ratio is also significant to the growth of microalgae and nutrient removal. Microalgae could adjust the N/P ratio in biomass according to the nutrient ratios in wastewater. The studies showed that a range of approximately 6.8-10 was preferable for microalgae to grow and remove nutrients. Choi and Lee found that the biomass production reached its maximum at the N/P ratio of 10 then decreased as the N/P ratio continuously increased, and the trend of TP removal rate was consistent with the biomass productivity. The nutrient removal rates can be improved by mixing different types of wastewater. Lu et al. mixed different types of meat processing wastewater. And when C/N and N/P ratios were balanced in 3.7 and 7.1 respectively, TN (50.94%) and NH_4-N (90.38%) removal rates achieved the highest [28].

2.4.3 Cultivation mode and symbiosis

Microalgae have three cultivation modes: Autotrophy, heterotrophy, and mixotrophy. The differences between them are the way of utilizing light, or carbon, or both of them to synthesize organic substances through photosynthesis. Comparing to autotrophic cultivation, heterotrophic cultivation has higher biomass productivity and higher COD removal rate supported by the higher carbon source concentration with no demand for light and easier to be harvested, and mixotrophic cultivation can mitigate climate change with higher nutrient removal rate and biomass productivity.

Besides, culturing microalgae and bacterial in one system has a mutual effect to enhance the performance of microalgae. Fig.3 illustrates the beneficial interactions between autotrophic microalgae and heterotrophic bacteria concerning the exchange of oxygen and carbon dioxide. In the co-existing system, the nutrient removal rates and biomass productions of both microalgae and bacteria will be higher. However, the competitive relationship between some types of bacteria and microalgae could also inhabit the performance of both of them.

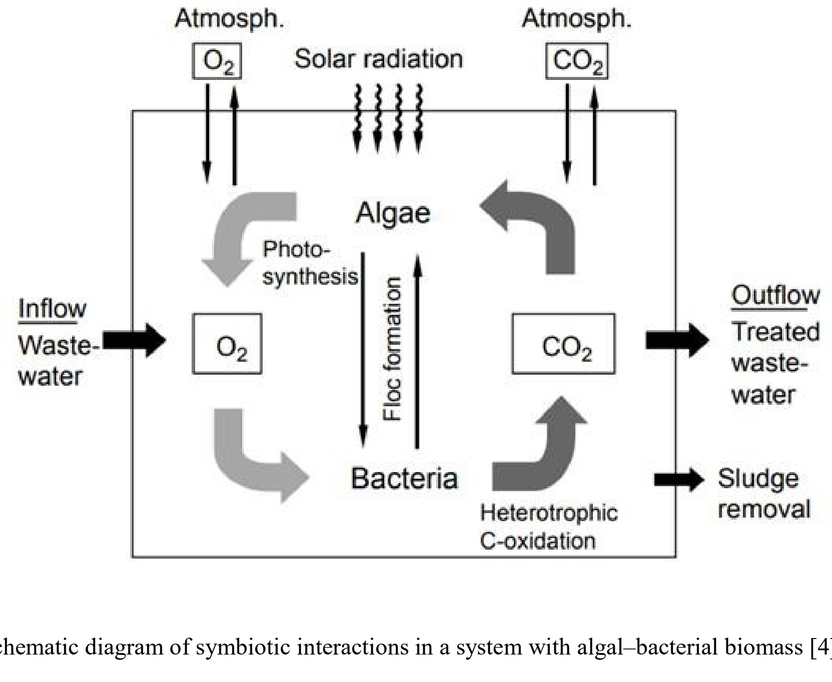

Figure 3. Simplified schematic diagram of symbiotic interactions in a system with algal–bacterial biomass [4].

2.4.4 Wastewater properties

In addition to nutrient ratios, other wastewater properties, such as pH, temperature, toxic substances, etc., could also significantly influence the growth of microalgae, nutrient removal rates, and biomass productivity. The study showed that the pH lower than 8 would limit the volatilization of NH3 and the precipitation of phosphorus appears when pH > 9. Adding additional CO_2 could help microalgae to remove nutrients [29]. Different microalgae species have different abilities to adapt to temperature, such as Chlorella sp. and Scenedesmus sp. can adapt to the temperature of 5 to 42.5 degrees Celsius, and the most favorable temperature for microalgae can be 15 to 37.5 degrees Celsius [30, 31]. Toxic substances, such as heavy metals, aldehydic and phenolic compounds, could threaten the survival of microalgae and affect the process of biomass production.

2.4.5 operation parameters

Unlike batch culture mode, in continuous culture mode, HRT is an important factor affecting the performance of microalgae. Arcila and Buitron [32] studied the nutrient removal rates of actual municipal wastewater with different HRT in algal-bacterial systems, and the results showed that when HRT increased from 2 days to 6 or 10 days, the effectiveness was optimal, of which the removal rates of COD, NH_4-N and TP was higher than 92%, 85%, 30%, respectively. However, HRT is not the higher, the better because of the cost. In addition, in the actual culture process, the degree of stirring, the frequency of microalgae harvest are all important factors affecting the performance of microalgae.

3. MICROALGAE-BASED WASTEWATER TREATMENT SYSTEM

MBWT system plays an important role in the application of MBWT technology and has been continuously moving forward to achieve high nutrient removal and recovery, lower cost and lower energy consumption, and so forth. Conventional MBWT systems include open raceway ponds (RPs) and enclosed photobioreactors (PBRs). Although RPs and PBRs are more available in the application for their convenience, they also have many drawbacks. For instance, RPs have low nutrient removal rates and biomass productivity, and PBRs are hard to settle down and harvest. Therefore, many hybrid MBWT systems have been developed to address these issues.

3.1 Conventional MBWT system

3.1.1 Open raceway ponds

The open raceway ponds (RPs) are the oldest, inexpensive, and most commercialized large-scale microalgae culture systems in industrial application. High-rate algal ponds (HRAPs) are a representative type of open ponds based on raceway configuration. Comparing with RPs, HRAPs are normally equipped with paddle wheels to help mix water to keep the circulation of microalgae culture and prevent the precipitation of biomass. Dahmani et al. studied using *Chlorella pyrenoidosa* to treat domestic wastewater in an RP. The results showed that the average biomass production could achieve 1.71 gL^{-1} with COD (78%), TN (95%), and TP (81%) removal [33]. However, there are some drawbacks of the traditional open system such as contamination in the atmosphere and other microorganisms, water evaporation, large space requirement, low biomass productivity, and nutrient removal rates, difficulties in adjusting operation parameters.

3.1.2 Enclosed Photobioreactors (PBRs)

PBRs are the enclosed, suspended microalgae cultivation systems. Comparing to RPs, PBRs are more efficient in controlling operation parameters (irradiation intensity, mixing intensity, CO_2 supply, aeration flow rates, temperature, pH, etc.) [34] and monitoring physiological conditions in a smaller space with less risk of contamination, and can be designed and modified according to the needs of different microalgae strains. The commonly applied PBRs include flat-panel PBRs, tubular PBRs, column PBRs, soft-frame PBRs. Among all of them, Tubular PBRs are the most commonly applied configurations at an industrial scale. PBRs are the most effective cultivation systems for the biomass productivity of microalgae. However, PBRs are expensive in construction and maintenance, so they are normally used in treating some types of wastewater with the production of high commercial value-added compounds, and the cost can be lowered by using efficient and lower-cost materials. Another key issue associated with PBRs is that penetration of light is limited on the surface of PBRs where the microalgal biofilms form. This problem can be resolved by using a better design of PBRs. Shi et al. designed a twin-layer PBR and achieved high nutrient removal rates and high biomass productivity (6.3 $g/(m^2 \cdot d)$) [35]. Other designs like multi-layer PBRs and some hybrid PBRs can also help to address this issue.

3.2 Hybrid MBWT system

3.2.1 Membrane photobioreactor (MPBR)

PBRs are recently combined with membrane filtration processes, from which the system can produce highly concentrated biomass along with efficient nutrient removal, which also resolves the poor settle ability, loss of biomass, and difficulties in the harvesting of PBRs. The excess biomass harvested from the system is then sent for further processing, including nutrient extraction or biofuel production. Research conducted by Y. Luo et al. [36] comparing PBRs and MPBRs overall performance showed an improvement by MPBR in almost every aspect. Dilution rate (D) played a crucial role and significantly affecting the nutrient removal efficiency. The PBR only allowed a dilution rate (D) (day^{-1}) below 0.2, while

MPBR obtained higher dilution rate in a wider range (0.2-0.8), which provided an increase in both biomass concentration and productivity. However, both PBR and MPBR could reach 80% removal rate for N and P with D at 0.2 and 0.3, respectively, and as dilution rate rises, removal efficiency dropped dramatically. Thus, choosing optimum dilution rate is crucial to simultaneous biomass production and nutrient removal. Another study comparing two kinds of MPBR with different membrane technology: (1) micro-filtration-based MPBR, (2) and forward osmosis-based osmotic MPBR (OMPBR) showed a better water treatment potential for OMPBR than MPBR systems. OMPBR has achieved 86-99% nitrogen removal efficiency and 100% phosphorus removal efficiency, whereas MPBR was 48-97% and 46%, respectively. But both systems received a high biomass concentration of more than 2g/L [37].

Comparing to PBRs, the integration of membrane units (MBR) provides separation of Hydraulic Retention Time (HRT) and Solids Retention Time (SRT), from which the system could achieve high concentration while preventing essential biomass loss with smaller footprint. This also benefits the nutrient removing process, considering fewer N and P concentrations in municipal wastewater. In addition, the microalgae harvesting cost is reduced because of relatively high concentration. These advantages show that MPBR would be promising system and deserve to scale up for MBWT process in the future.

3.2.2 Anaerobic co-digestion (ACoD) of microalgae and sludge

An-MBR (Anaerobic Membrane Bioreactor) system has been one of the popular technologies as a feasible alternative to conventional treatment for energy recovery and reduction in sludge production. It mainly consists of two processes. Firstly, wastewater is treated in an anaerobic environment where large organic particles are decomposed by anaerobic bacteria, producing biogas consisting of 60-65% methane and 30% CO_2 and biosolid. Then the treated effluent goes through an artificial membrane, which filters out the treated water for further use, and the retentate is sent back to the anaerobic tank. However, The AnMBR effluent presents high nutrient concentrations, which can be recovered by microalgae cultivation. These microalgae could be later anaerobically digested to achieve anaerobic co-digestion (ACoD) with various types of sludge, giving rise to a digested sludge enriched in nutrients and energy that could be recovered. A study conducted by Serna-Garcia, Ruiz-Barriga et al. [38] said a total of 78 L day^{-1} of biogas production consisting of high concentration (69%) of methane is monitored. An overall 99% of N recovery by Hollow- fiber membrane contactor (HFMC) is achieved regardless of membrane cost, producing a solution that can be used for chemical fertilizers. The P transformation is divided into two parts: (1) 74% of available P is converted to struvite inside the reactor, and (2) 26% of P is left in the effluent after ACoD process. Furthermore, nutrient recovery is achieved in this process as three potentially useful by-products were generated through microalgae and primary sludge co-digestion in an An-MBR: methane-rich biogas, nitrogen-rich permeate, and nutrient-rich digestate. Nutrients left in the treated effluent requires further post-treatment to remove. This integration represents a co-substrate consisting of microalgae biomass and primary sludge for the anaerobic digestion (AD), and the permeate is later treated by composting. Through this process, nitrogen and phosphorus are recovered first removed from the effluent and allowing potential recovery along with methane production AD generates biogas mainly consisting of methane). ACoD system is still in pilot- scale, thus no actual usage had been reported.

High biomass and biogas production from microalgae, and less sludge was obtained in long-term ACoD of microalgae and sludge without the need to apply costly pre-treatments to improve microalgae degradation. Generally, this system provides a potential complete removal of nutrients and self-sufficient of energy in the Wastewater Resource Recovery Factory (WRRF).

3.2.3 Microalgae biofuel cell (MFC)

MFC has been widely studied for its outstanding performance in both wastewater treatment and also achieving energy recovery with exoelectrogens in the bioelectrochemical process, which is also known as integrated photobioelectrochemical system (IPB). As the electron transformation process is oxygen consuming for maximization of efficiency, the microalgae are grown in the MFC with the wastewater as co-substrate, from which the algae will generate oxygen to support the bacteria cathodes to produce electricity while consuming organic compounds, and the algae can also contribute to the removal and potential recovery of inorganic nutrients. In the experiment of Xiao et al., the ammonium nitrogen and phosphate recovery rate reached 98% and 82% in 128 mg/L of algal biomass [39]. She also studied that the oxygen production by algae provides enough aeration of bacteria, especially at night with the value of dissolved oxygen dropping from 20 mg/L to less than 1 mg/L. The increase in oxygen supply will also increase the efficiency of electricity production. With more oxygen-depleted, the maximum current is boosted. Another novel microalgae-bacteria-powered biofuel cell developed by Jian Sun et al. highlighted for aquaculture wastewater treatment can achieve efficient nitrogen removal (99%) and electricity generation (around 0.02A) while accelerating the degradation of antibiotic florfenicol (FLO) [40].

The integration of microalgae with bacteria in an MFC system contributes to four aspects: (1) organic feedstock to support bacterial growth, (2) assisting anode bacteria to generate electricity, (3) providing oxygen from photosynthesis as a cathode electron acceptor, and (4) removing N and P from effluent water. This also decreases the intense competition between microalgae and bacteria, which could benefit specific dominant algal taxa selection and cultivation of particular contaminate removal, including antibiotics and some refractory organics.

3.2.4 Rotate algal biofilm reactor (RABR)

Rotate algal biofilm reactor (RABR) culture system has been developed for attached algal growth, which has been shown to be effective at growing concentrated algal biomass with easy harvesting. The RABR system consists of a revolving belt that algae cells attach to and a liquid reservoir that supplies nutrients and keeps the algae moist. The RABR usually consists of cylinders that provide the growth surface for microalgae and are partly immersed into the wastewater. The cylinders are rotated during the operation to ensure the biofilm on the growth surface being exposed to both wastewater and air alternately. The main advantage of using rotating algal biofilm reactors (RABR) is the reduced cost for harvesting and the high productivity due to light dilution in time.

Microalgae have been commonly grown in open ponds or photobioreactors. In these systems, the cell densities are generally low (between 0.5–6 g/L or 0.05–0.6% solids). Following growth, specialized harvesting and dewatering operations, which are costly and can be very time-consuming. Biofilm-based culture systems have proved to be effective in reducing the expensive algae harvesting operations. Algae are attached to the surface of a material and are easily harvested via scraping. When harvested, the algal paste already has a water content similar to post-centrifuged algal biomass (80–90%). Thus the expensive harvesting and dewatering steps can be avoided. Indeed, cells are never too long in the sunlight, so that photoinhibition (damages due to excess light energy) is mitigated. The time microalgae are exposed to light affects their growth; that is, after a longer exposition to high light intensity, the cells become photo-saturated and often inhibited. Photoinhibition is characterized by the denaturation of some key proteins contributing to photosynthetic activity. RABR offers the possibility to regulate light distribution through the biofilm by varying the rotational speed and therefore changing light exposure. The rotation also allows the biofilm to be in periodic contact with the growth medium and maintains a high water content.

4. SUGGESTION AND PROSPECTS

There have been reviews focusing on next-generation MBWT with microalgae-based technology. However, the defect of this brand treatment is still obvious. First of all, most of the reviews and experiments of the MFC are laboratory scale and are still problematic. The challenges of this configuration are facing are: 1) the addition of algae in the MFC system will be a cost-effective choice, but the design of the overall system will be an issue, 2) the system will be complicated to manage since numerous factors are involved, including anaerobic digestion (AD) which can affect the electricity generation and high cost of original MFC with the algae system. When the integrated system is going to be scaled up for commercial use, these factors need to be considered. Secondly, the fouling issue and cost concerning efficient continuous functionality of the membrane section are yet to be solved by cheaper and better material.

Modeling in wastewater will be effective for viewing the status of the reaction and offering a suggestion of adjustments of the system when an error happens. For example, there is acetate found in the system where the concentration of acetate indicates the substrate concentration and respiration, which further shows the efficiency of the overall MFC system. As modeling is just getting started, more attention is needed for further research and the establishment of basic modeling methods. Also, microalgae still represent a complicated aspect with various species and multiple influencing factors; combined wastewater treating function and mechanism requires further research.

5. CONCLUSION

The microalgae-based wastewater treatment showed significant benefits in comparison with conventional process, and its great potential in nutrient and energy recovery, net-zero emission, and biofuel production is showing a new trend of future WWTP. It also possesses adaptability treating different types of wastewater to maximize the ability to recover or remove. However, the problems, including system complications and lack of treating and economic efficiency, are still obstructing any successful business application.

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