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Research progress and application prospects of microalgae in photobioreactors

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Abstract

According to the current burden of greenhouse gases on the planet and the growing demand for products that follow sustainable development principles, the demand for bio-based products can be seen growing. These trends offer great possibilities for the use of microalgae, especially in the pharmaceutical sector, the food industry and the production of biomass energy feedstocks. In the pharmaceutical and food industries, products entering the market with high added value can often be predicted, which offers a wide range of possibilities for microalgae production applications. Microalgae also have high potential in wastewater and industrial waste gas treatment.

Keywords

Dye wastewater;Decolorization; photobioreactor.

1. Design and application of photobioreactors

1.1. Plate Photobioreactor

This type of photobioreactor has a high specific surface area and has obvious advantages in light energy utilization [1]; secondly, plate photobioreactors have relatively minimal mechanical requirements and less energy consumption [2]; the study found that the plate photobioreactor can reduce problems such as biological sedimentation or leakage while increasing the biomass production [3].

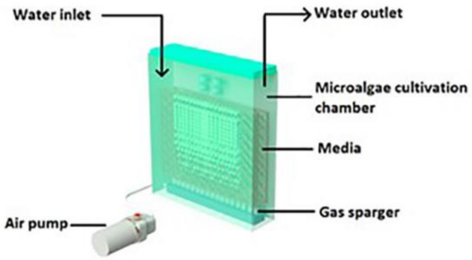

Fig. 1 Plate bioreactor

It was reported that Shi and researchers [4] achieved 70%-99% removal rates of nitrogen and phosphorus through the double-layer plate photobioreactor, and the nitrogen and phosphorus concentrations in the treated wastewater were lower than 1.3 mg/L and 1 mg/L, respectively. which are 3 times and 2 times the treatment efficiency of the open pond system of Boelee et al. [5], respectively, and meet the discharge standards of the European Water Framework Directive (the maximum absorption of nitrogen and phosphorus is 1.0 and 0.13 g/L, respectively [6]. Plate photobioreactors can also be used for CO_2 removal, and Martín-Girela et al. [7] improved CO_2 adsorption in a plate photobioreactor up to 0.125 molCO_2/μmol.

1.2. Column photobioreactor

Column photobioreactors are usually constructed vertically. By aerating the culture with air or carbon dioxide gas, the process of thorough mixing takes place. This type of photobioreactor has adequate gas-liquid mass transfer, biomass yield and light/dark cycle control [8]. Column-type photobioreactors are simple in structure and can be connected by modules or combined with other technologies, especially membrane processes.

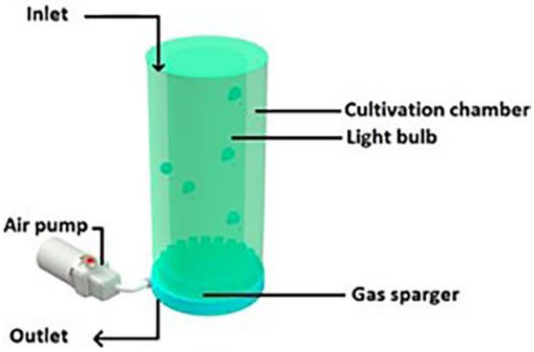

Fig. 2 Column photobioreactor

In terms of pollutant removal, columnar photobiological reaction is a commonly used method to remove pollutants. Arias et al. [9] found that in a closed column photobioreactor, the proliferation of various microorganisms and microalgae could be promoted by adjusting the ratio of different culture components. Total inorganic nitrogen/inorganic phosphorus (21 mg N/L and 2 mg P/L), sufficient C supply and P content enabled cyanobacteria to proliferate continuously for 234 d. Lee et al. [10] believed that longer dark conditions favored carbon uptake, while nitrogen and phosphorus consumption tended to favor light conditions, with chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (The removal rates of TP) were 59.8%, 35.9% and 43.9%, respectively. Since nitrifying bacteria inhibit the growth of microalgae, photobioreactors that inhibit the nitrification process can achieve higher growth rates and chlorophyll content. Zhang et al. [11] improved the nutrient removal efficiency through the microalgae and bacterial communities, and the microalgae enhanced the bacterial proliferation activity, and the maximum removal rates of COD, TN and TP were 96.7%, 70.5% and 96.4%, respectively.

The internal carbon source of the photobioreactor not only comes from wastewater, but also includes CO_2 in the industrial emission environment or polluted air. Chen et al. [12] cultivated microalgae with gas from power plants, and the results showed that spirulina can absorb 2234 kg CO_2 per year, which is equivalent to 74 tons per year. In addition, common microalgae in the columnar photobioreactor also consumed 80% of the CO_2 in the carbon source [13]. In a similar application, Jacobs-lopes et al. [14] developed operating methods for the removal of carbon dioxide in bubble columns and airlift photobioreactors. The air circulation method is suitable for small-scale treatment, and the two-stage sequential photobioreactor method is suitable for industrial scale. When the inlet CO_2 concentration was 15%, the removal rate and loading exceeded 52.5% and 12.217 g carbon/m^3reactor•d[15], respectively.

1.3. Tubular photobioreactor

Tubular photobioreactors are available in a variety of designs, including curved, horizontal, vertical, and helical. They are arranged in arrays/layers together or next to each other. These arrays/layers are connected and mixed by a pump or aeration system. Therefore, the tubular photobioreactor has sufficient contact time for mass transfer.

Gómez-Pérez et al [16].applied wall turbulence promoters in tubular photobioreactors to reduce mixing energy consumption. Tubular photobioreactors with a flow rate of 0.1-0.3 m/s can save

60-80% of the energy consumption rate compared to traditional photobioreactors [16]. Tube photobioreactors involve many operating parameters (such as tube arrangement, DO, nutrient ratio, energy and lighting) and are relatively more complex than other types of photobioreactors. Henrard et al. [17] applied batch operation mode in tubular photobioreactor with appropriate mixing concentration (1.0 g/L), medium renewal rate (30-50%) and bicarbonate concentration (1.0 g/L) The combination can obtain the expected biomass yield, which solves the high cost of batch operation and is beneficial to the development and progress of future industrialization

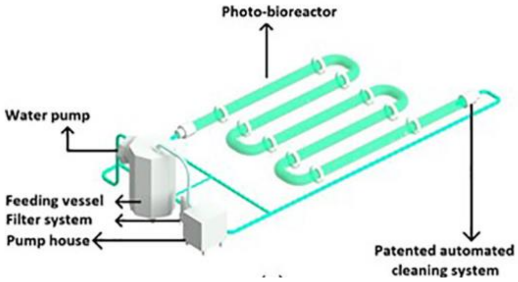

Fig. 3 Tubular photobioreactor

Slegers et al. [18] studied the effects of reactor size, light intensity, and microalgal biological performance on horizontal and vertical tubular photobioreactors. It was found that the decolorization rate of the vertical tubular photobioreactor was nearly 70% under the same conditions, while the decolorization rate of the horizontal tubular photobioreactor was only about 30%. It is speculated that the vertical photobioreactor has a higher decolorization rate than the horizontal photobioreactor. In addition, geographic location also affects the efficiency of photobioreactors. [19] proposed that using reflective materials on the ground, bringing more illumination, can improve system performance. The disadvantage of tubular photobioreactors is that considerable power is consumed due to prolonged mixing of the media in the connecting tubes. In addition, a twisted-tube photobioreactor with swirl flow is proposed, which reduces energy consumption by 38%-77%.

Compared with other types of photobioreactors, tubular photobioreactors have less applications in pollutant removal, and the types and quantities of pollutants reported to be treated are also limited. In a laboratory-scale tubular photobioreactor, Binnal and Babu [20] reported the highest CO_2 fixation rate of 273.66 mg/L•d under the condition of insufficient nitrogen content. The optimal operating conditions were determined by response surface methodology as follows: pH 6.51, temperature 28.63 °C, light intensity 5.31 klx, photoperiod 15.36:8.64 h, CO_2 concentration in the air 6.26% (v/v), and aeration rate 2.92 lpm. For the removal of daily pollutants, Kang [21] et al. used photobioreactors to degrade domestic sewage in their studies. It was found that BPA was largely removed with a removal rate of 72%-86.4%, while the removal rates of hydrochlorothiazide, ibuprofen, carbamazepine and gemfilozil were lower at 6.45%-48.7%. It is speculated that the effect of microbial community on pollutant removal is greater than that of microalgae, and periodic and low irradiance illumination affects the degree of pollutant removal.

1.4. Hose Bioreactor

Most photobioreactors are made of rigid materials and are permanently fixed throughout their service life. Tube photobioreactors are space saving, flexible, foldable and mobile. They are designed to hang on a shelf, float on water or lay on the ground in a range of designs. The choice of materials of manufacture also varies, including ethylene vinyl acetate/low density polyethylene (EVA/LDPE), polyethylene and polytetrafluoroethylene (PTFE). Compared with other photobioreactors, the application of hose photobioreactors is limited, but it has become more and more popular in recent years. Hamano et al. [22] attached microalgae to cellulose sheets or Teflon membranes in a laboratory-scale hose photobioreactor, and then cultured them in the photobioreactor. Nutrients are provided by the capillary mechanism of cellulose flakes. Therefore, mixing does not require energy. But the high cost of PTFE materials limits the commercialization of this technology. Chemodanov et al. [23] tried to apply the hose photobioreactor to buildings, using sunlight as a lighting source. Growth rates, however, have fluctuated widely for unknown reasons. Under a similar concept, Hom-diaz et al. [24] and García-Galán et al. [25] constructed full-scale hose photobioreactors for toilet wastewater and agricultural drainage treatment, respectively. Due to the large energy consumption of the tube photobioreactor, Jones et al. [26] optimized the tube photobioreactor to reduce the energy consumption. Surface aeration and rocking platform mixing methods are used instead of injection. The power input was 5763.3 W/m^3, which did not affect the growth of microalgae.

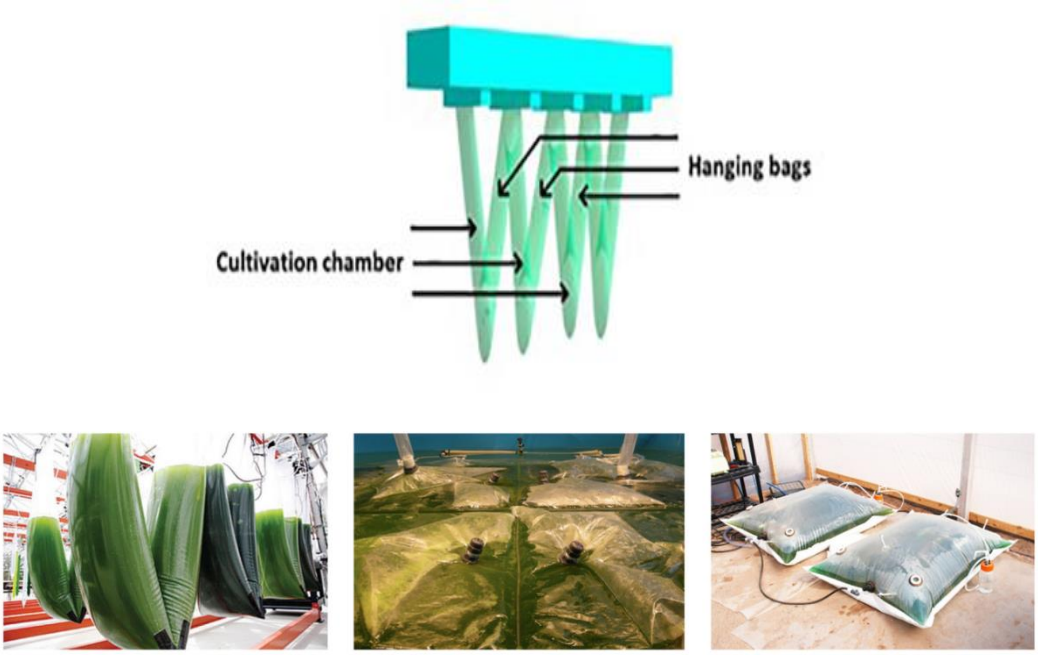

Fig.4 Hose bioreactor

Similar to tubular photobioreactors, there is less previously published literature on contaminant removal by tube photobioreactors. It is likely that the hose photobioreactor is beneficial for the cultivation of microalgal biomass production rather than for pollutant treatment. In a full-scale hose photobioreactor, Hom-diaz et al. [27] reported over 80% removal of N-NH^{4+}, TP and COD in toilet wastewater. For removal of daily pollutants, including anti-inflammatory drugs (ibuprofen, acetaminophen, salicylic acid and codeine) with 98% removal efficiency, diuretics hydrochlorothiazide (84%) and furosemide (100%)[28]. Antibiotics, such as ofloxacin, erythrocin, etc., can only be removed about 48% in this photobioreactor [28]. Parladé et al. [29] reused the photobioreactor system designed by Hom-diaz et al. [28] to evaluate the efficiency of microalgae-bacteria co-culture to remove 17β-estradiol. Parladé et al. [29] found that 17β-estradiol was completely removed within 12 h. However, estrone was detected as a metabolite. García-Galán et al. [29] studied a hose photobioreactor for the treatment of agricultural wastewater. The results showed that the removal rates of N and P by the photobioreactor were 84% and 95%, respectively. The main factor influencing the removal of contaminants under the influence of sunlight exposure under outdoor conditions. García-Galán et al. [29] used a photobioreactor to remove synthetic musk scents, such as musk tonneau and musk gala, by 73% and 68%, respectively, while anti-inflammatory compounds (such as diclofenac) were eliminated by 61% after 4 months.

These photobioreactors were originally called horizontal multi-tube photobioreactors. However, due to their foldable and flexible material, they can also be classified as hose photobioreactors. Tube photobioreactors have broad application prospects and potential for industrial production, but there are also some shortcomings, including insufficient lighting efficiency, material cost and lifespan. Inadequate mixing is another challenge due to the formation of closed dead zones inside.

1.5. Hybrid Photobioreactor

Hybrid photobioreactors here refer to the combination or integration of the above four photobioreactors or with other technologies (such as membrane processes), resulting in a reduced volume of photobioreactors, higher biomass production, and removal of pollutants. better result. Hybrid photobioreactors were developed using the advantages of traditional photobioreactors [30]. Soman and Shastri [31] designed a new design combining the advantages of flat plate and tubular photobioreactors. The tubular area is operated in a cylindrical core of a rectangular tube, while the two surrounding baffles are attached to the tube and function as a flat plate structure. This type has a 7% surface to volume ratio and a premium flow regime. The light/dark frequency is 0.14 Hz, which is superior to conventional light/dark frequencies and reduces operating and material costs for further optimization. Given the advantages of attached culture over suspension culture in biomass harvesting, Xu et al. [32] proposed a capillary-driven photobioreactor that transports nutrients and moisture into polyester microfiber medium by capillary action , to overcome the limitations of biological harvesting in traditional suspension culture. Therefore, the reactor obtains a higher content of lipids and carbohydrates suitable for the production of biofuels.

Other innovative types of photobioreactors have also been developed to reduce reactor size and maximize biomass production. These designs and techniques are suitable for different geographic locations. Dogaris et al. [33] developed a floating horizontal photobioreactor on plastic films in a modular configuration. It consists of attaching two layers of plastic films on the upper and lower surfaces of the photobioreactor, which are sealed to each other, and having two vertical airlifts attached to the films[34]. achieved high-capacity performance of thin-film photobioreactors during fermentation. The thin culture layer (1.5-2 mm) provides a light area of up to 500 m^2/m^3 through an intensification mechanism. Similarly, adding a light guide plate modified with silica chitosan medium in the photobioreactor can improve the production of biological hydrogen.

The combination of biofilm and photobioreactor is called membrane photobioreactor. For example, Chang et al. [35] designed an ion-exchange membrane photobioreactor, which divided the wastewater source and microalgae into different chambers, and N^+ and P^{6+} entered the microalgae chamber through the ion-exchange membrane. The design mitigates the negative effects of pollutants in wastewater on the growth of microalgae. However, the high cost of ion-exchange membranes is a major constraint for their application, and membrane fouling is a major technical problem in MPRs. In recent years, research on how to deal with membrane fouling has become more and more intensive. For example, the study found that the fouling rate of ceramic membranes was more significant when the HRT was 6.5 h than when the HRT was 24 h and 72 h, and the combination of microalgae and the sludge bioreactor alleviated the fouling of the hollow fiber membranes. Oxygen released by algal photosynthesis reduces bacterial mortality, thereby alleviating membrane fouling. For large-scale applications, Viruela et al. [36] fabricated a membrane photobioreactor consisting of a flat plate photobioreactor and a fiber ultrafiltration membrane. In addition, Sheng et al. [37] also established a photobioreactor method to treat secondary effluent wastewater.

The utilization and combination of membrane and photobioreactor technologies can significantly improve the efficiency of nutrient removal. The biofilm photobioreactor removed

82.5% and 85.9% of TN and TP in the secondary effluent, respectively [38], and the removal rate was higher than that of the conventional photobioreactor. Membrane photobioreactors can also retain microalgae, resulting in lower concentrations of suspended solids in the effluent. In another study, the hollow fiber microfiltration membrane photobioreactor designed by Gao et al. [39] achieved 86.1% and 82.7% removal rates of TN and TP in aquaculture wastewater, respectively. The ammonia concentration in the effluent is as low as 0.002 mg/L. Subsequently, the operation of this MPR was optimized by adjusting the HRT and biomass residence time to 2 d and 21.1 d, respectively [40], and the removal efficiency of TP was increased to 90.8%.

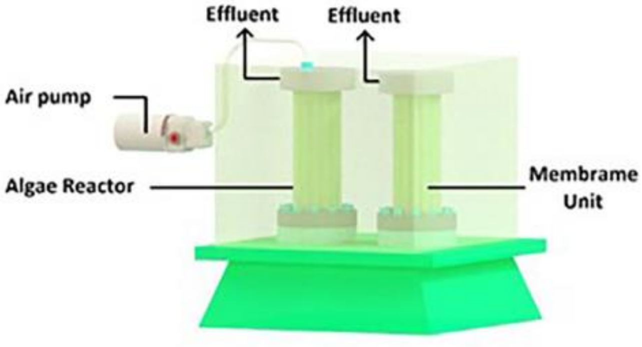

Fig. 5 Mixed photobioreactor

2. Development of photobioreactors

A variety of innovative structures have been developed for photobioreactors, such as multi-column structure, modular plate structure, hybrid structure, etc. [41]. But high energy costs and demanding local conditions (temperature, light and climate) are the main constraints. The combination of microalgae-based photobioreactors and buildings is a new trend in green buildings in recent years. Of these configurations, flat-panel photobioreactors are the most common architectural and infrastructure designs. To construct a photobioreactor-based building, microalgae-based flat-panel photobioreactors are fully deployed on the building's façade. By doing this, there is ample sunlight and temperature that favors the growth of microalgae and also creates shade for the interior of the building. In addition, photobioreactors can retain thermal energy and return it to the building.

Pruvost et al. [36] of Nantes, France integrated vertical flat-panel photobioreactors into building façades, an approach that helped increase solar lighting and use the carbon dioxide produced by the building to cultivate microalgae. With the thermal regulation process, the total energy consumption is reduced by 70%. However, its energy balance is still negative. Chemodanov et al. [40] also integrated hose photobioreactors into buildings. This strategy was aided by software [27], a geographic information system that assessed the energy production capacity of two types of flat-plate and tubular photobioreactors. Subsequently, they were integrated into the built environment and the energy balance was analyzed by building information modelling, but there was no experimental data to validate the model. With the help of green solar collectors or dye-sensitized solar cells, photobioreactors can receive more sunlight, which can solve the shortcomings of insufficient sunlight in low latitudes. The devices can operate with large fluctuations in the sun's angle and increase sunlight capture efficiency by 89 percent. Researchers such as Eltayeb et al. [20] and Lee and Han et al. [19] developed photobioreactors as a sustainable concept with zero waste emissions.

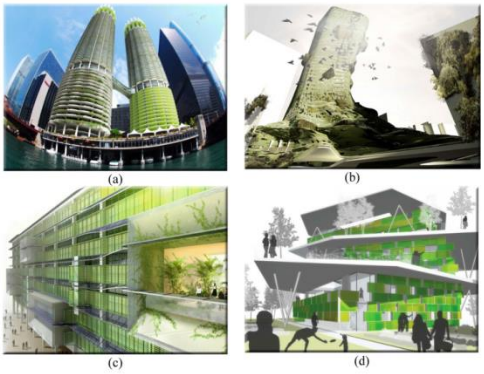

Fig. 6Future development of algae-based buildings and infrastructure.(a) the Green Ring Road (b) the self-sustaining Tower in London.(c)GSA Federal Building (d) Hydroelectric Residential Unit with Modular Hydrogen Production Panels

Further research and refinement of these building designs could generate income from biomass and by-products while treating and reducing pollutants. The combination of photobioreactors and building structures makes photobioreactors promising prospects, which have the following advantages: ① Waste from other processes can be used as input to the photobioreactor ② Centralized operation and control of the process ③ Through the production of multiple energy to heat and insulate the interior of the building, thereby reducing costs. According to reports, the building contains multiple functions such as bioenergy production, heating, and algae cultivation, which is a technically complex and expensive project. Whether the building can be constructed at high latitudes has also raised concerns due to the effects of low temperatures on algal growth.

3. Conclusion

Although the performance of photobioreactors is promising in laboratory and pilot-scale environments, industrial-scale photobioreactors still require a lot of research and improvement. Current research is carried out by research institutes and small private companies, so research for large-scale industrial applications is limited. For example, flat-panel photobioreactors are integrated with single-use plastics. This particular system required frequent replacement of the plastic due to serious problems such as leaks, dirt and overheating. The high cost of microalgae harvesting, biofuel production, and mixed energy consumption is another indirect reason hindering the development of industrialization. In addition, industrial photobioreactors require sufficient reactor volume and sufficient material sources, but excessively large reactors and depth hinder light transmittance and mixing efficiency. With further development of photobioreactor designs, coupled with strong support from modeling tools, operating conditions will function more efficiently. Currently, the process is still in the trial and simulation phase. For example, modeling was used to upgrade the design of flat-plate and tubular photobioreactors; Fuente et al. also developed scalable lighting modeling, suggesting a modeling approach when more than six variables are considered. , rather than experimental work. While the reactors used for the mixed growth of yeast and bacteria have standard geometries, the reactors used for the cultivation of microalgae are still relatively complex. As an environment- and energy-friendly strategy, the industrialization of photobioreactors has broad prospects for development.

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