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The research status of several technologies capable of integrating wastewater treatment with carbon capture

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Abstract. Since the Paris Agreement was proposed, many industries need to make efforts to save energy and reduce emissions. It is understood that the sewage treatment industry accounts for about 3% of global greenhouse gas (GHG) emissions, and with the acceleration of urbanization and industrialization in some countries, the total sewage treatment capacity will further increase. This will also lead to a further increase in the industry's greenhouse gas emissions, exacerbating global climate change. Therefore, the sewage treatment industry needs to make technical changes, but under the premise of not affecting the effect and efficiency of sewage treatment. Under such basic requirements, technologies that combine sewage treatment with carbon capture have gradually emerged in recent years. This review selects 3 technologies, including microbial electrosynthesis (MES), constructed wetland and microalgae cultivation, with good development prospects in this area, then summarizes their carbon capture principles and capabilities, sewage treatment principles and capabilities, research status in recent years, and current problems, in order to provide some ideas for the carbon emission reduction plan of the sewage treatment industry.

1 Introduction

In 2016, the Paris Agreement signed by various countries officially began to implement. The objective is to keep the increase in the average world temperature below 2 degrees Celsius compared to the pre-industrial era and to keep it below 1.5 degrees Celsius before the year 2100. In recent years, many industries have done a lot of basic research on energy conservation and emission reduction in order to comply with the content of the Paris Agreement, such as the energy and transportation industries that account for a large proportion of carbon emissions.

The sewage treatment industry also accounts for a large part of the contribution of global carbon emissions. Its carbon emissions mainly have two parts, one is the direct GHG emissions produced in the process of sewage treatment processes such as Anaerobic-Anoxic-Oxic and activated sludge process, and the indirect carbon emission produced due to energy consumption in the operation of sewage treatment plants. CH_4 and N_2O emissions from the wastewater treatment industry accounted for 5.17% and 3.49% of the global emissions budget, respectively [1,2]. Its energy consumption is also close to 3% of global electricity consumption [3]. Not only that, with the acceleration of industrialization and urbanization in various places, the amount of sewage that needs to be treated will increase, and the requirements for effluent will become more stringent. This means that if the carbon emissions of the sewage treatment industry are not controlled, they will further increase in the future.

In the process of sewage treatment, it is necessary to degrade the pollutants that are harmful to the environment, such as organic matter and nutrients in the sewage, so as to meet the effluent conditions that need to be met. Greenhouse gases such as carbon dioxide are included in the degradation products, which is inevitable. Therefore, in the method of reducing carbon emissions in sewage treatment, carbon capture is dominant.

In this context, it is necessary to make changes to the relevant technologies of the sewage treatment industry, so as to limit the emission of greenhouse gases without affecting the effect of sewage treatment. Therefore, some technologies that can combine sewage treatment with carbon capture have attracted the attention of scholars in recent years. After screening, it was found that microbial electrosynthesis (MES), Microalgae cultivation, and Constructed wetlands have achieved outstanding research results in recent years and can meet the background requirements. If these technologies can mature, it is hoped that in the future, it will change the current status of high carbon emissions in the sewage treatment industry, and may even become an important contributor to global negative carbon emissions [3]. Therefore, the following will introduce the basic content of these three technologies in order from the basic principles, current research progress, existing problems, etc.

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2 MES

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MES is one of the technologies for biological capture of CO_2. It can use the biological reaction of CO_2 and waste water or even waste gas to generate other usable organic matter. While capturing carbon dioxide, it can also treat pollutants in waste water and waste gas The specific reaction principle is: an oxidation reaction occurs at the anode to decompose water to generate electrons. Some of the electrons are utilized by the anode itself. Another part of electrons and hydrogen ions are transferred to the cathode through the external circuit and the proton exchange membrane, and in the cathode chamber, the microorganisms adsorbed on the biocathode consume electrons and hydrogen ions to undergo a CO_2 reduction reaction [4].

If this technology can be widely applied in industry, it can capture a large amount of carbon dioxide produced in industrial production. It is a promising technology for carbon capture and provides technical support for carbon neutrality. In addition to that, this technology also has a certain ability to treat organic matter in wastewater. If it can continue to develop, it may be able to replace some processes in the existing sewage treatment method (such as activated sludge method), thereby reducing the amount of carbon dioxide in the process.

The main factors affecting the performance of MES are: cathode material, potential, temperature, pH [5]. Since the cathode reaction is the core content of MES, the selection of its material is very critical. At present, the most widely used cathode material in MES is carbon-based materials, but the electron transfer efficiency of basic carbon-based materials is not ideal, so it is necessary to modify the materials, which is also the current mainstream research direction. For example, Aryal et al. prepared carbon felt (CF) cathodes coated with 3D-graphene (G) by a solvothermal synthesis process. Compared with the unmodified electrode material, its specific surface area was increased by 2 times, allowing more cells to attach to the 3D-G-CF electrode, resulting in a 6.8-fold increase in the rate of acetic acid synthesis [6,7]. The use of catalysts to couple cathode materials is also an important direction for cathode modification.

MES technology has the potential to efficiently produce organic chemicals. At present, the products of MES are mainly short-chain fatty acids (SCFAs), and relevant studies have shown that SCFAs can be upgraded to medium-chain fatty acids [8]. In the future, with the advancement of technology, it is possible to synthesize more complex and cost-effective organic matter, chemicals and even good fuels. Because of this, wastewater is gradually being regarded as a renewable energy like wind and solar energy. But at present, this technology still has certain limitations. First of all, the products of the current MES method are mainly low-value methane, acetic acid, etc. Other valuable organic substances such as formic acid, ethanol, etc. are always produced with acetic acid, and the conversion rate is much lower than that of acetic acid. There are also some organic compounds with medium and high carbon chains that are currently unavailable. Recent studies demonstrate that, when compared to conventional procedures, only a small number of MES products, such as formic acid and ethanol, are economically competitive on the market [3,9].

To resolve this issue, a new process is necessary to convert CO_2 to target compounds. At present, the main ideas are: catalytic conversion of C1 waste gas and coupling secondary fermentation to produce MCFAs; and the metabolic process of microorganisms directly affects the production of products. There is therefore a need to better understand this effect and try to find ways to control it. Second, the extraction, fractionation, concentration, and purification methods used to produce MES products can make up more than 60% of the price of production. [10]. To achieve large-scale chemical manufacturing, it is vital to create cost-effective extraction and separation technologies because these costs must be kept under control if this technology is to be used on a wide scale [10]. In addition to the above limitations, there are several other problems in this technology: the various cathode materials currently used in this technology have limitations in terms of efficiency and stability, so it is necessary to find a suitable cathode material. This contributes to electron transfer and biofilm formation, thereby improving the efficiency and stability of the technology; MES is affected by many factors, and there are optimal operating conditions for the operation of the system, but the operating parameters have not been optimized. Operating conditions such as potential, pH, and temperature have a great influence on the performance of MES, so it is necessary to further explore the optimal operating conditions for system operation and find the optimal reaction environment for different bacterial groups.

3 Carbon capture in constructed wetlands

Constructed wetland is a comprehensive ecological system constructed by man, and its main function is to use the physical, chemical and biological effects of plants, soil and microorganisms to treat sewage. Wetlands are also the largest carbon pool in the world, with the highest carbon storage capacity, making a decisive contribution to the global carbon cycle [11]. Therefore, constructed wetlands not only have the ability to treat sewage, but also have a strong ability to sequester carbon. Constructed wetlands can replace some traditional sewage treatment plants with lower net carbon emissions, further reducing the contribution of the sewage treatment industry to global carbon emissions.

3.1 Utilization of waste water in constructed wetlands

There is no doubt about the ability of constructed wetlands to treat wastewater, and the research content in this area is also very rich. Much of the content is to study how to treat new types of wastewater or enhance wastewater treatment capabilities by improving the vegetation types and process design of constructed wetlands. For example, a study by A. Gholipour et al. in 2020 found that Horizontal subsurface constructed wetland is effective in treating wastewater rich in suspended solids discharged from the glass production industry. The removal rates of BOD_5, COD, TSS, TN and TP in wastewater reached 90%, 90%, 99.8%, 92.5% and 86.4% respectively [12]. The treated water samples can meet the standards for re-introduction into the production process.

3.2 Carbon sequestration in constructed wetlands

The carbon sequestration of constructed wetlands is reflected in two aspects. First, it can process organic carbon in wastewater and capture it in wetland sediments. At present, after the traditional sewage treatment plant degrades most of the organic pollutants in the wastewater into carbon dioxide, there is no carbon capture apparatus, but the carbon dioxide is directly discharged into the atmosphere. And the technological process of the sewage treatment plant consumes a lot of energy compared with the constructed wetland. According to statistics, the current electricity consumption of the sewage treatment industry accounts for about 3% of the total global electricity consumption, resulting in a large proportion of the carbon emission contribution of the sewage treatment industry [3]. Therefore, a large number of constructed wetlands can replace the role of sewage treatment plants with lower carbon emissions, thereby indirectly reducing carbon emissions.

Secondly, constructed wetlands can also directly capture carbon dioxide in the atmosphere through photosynthesis of plants, thereby contributing to carbon neutrality. But when wetlands are drained, emissions of two greenhouse gases, CO_2 and N_2O, are also high in the soil. Therefore, the current main research in this area focuses on how to reduce the emission of CO_2 and N_2O in constructed wetlands, so as to increase the net carbon capture of constructed wetlands. For example, Guo et al. found that adding biochar to constructed wetlands can reduce their CO_2 and N_2O emissions at the expense of slightly increased CH_4 emissions [13]. But since N_2O is the GHG that contributes the most to Global Warming Potential (>76.9%), biochar addition can increase the net carbon capture of constructed wetlands in aggregate [13]

4 Microalgae cultivation for carbon capture

Microalgae is a kind of miniature aquatic plant, which usually refers to the general term of microorganisms that contain chlorophyll a and can perform photosynthesis. Microalgae, like ordinary plants, can use photosynthesis to convert sunlight, water and carbon dioxide into oxygen and usable biomass. Compared with ordinary plants, the cultivation of microalgae requires less space, and the growth rate of microalgae is faster [14]. The current areal productivity of microalgae is usually around 15–30 gm $^{-2}$ d $^{-1}$ [15]. Because of this, it is more efficient and economical to cultivate a large number of microalgae for CCU than ordinary plants.

4.1 Utilization of waste water by microalgae cultivation

Various nutrients, such as N, P, etc., need to be provided during the cultivation of microalgae. These constant elements are exactly what need to be removed in wastewater treatment. Therefore, it is economically feasible to combine microalgae cultivation with wastewater treatment.

Microalgae are rich in cellular enzymes, which can fully absorb the nutrients in the treated wastewater and apply them to their own growth and biomass production [16]. Microalgae, for instance, can use nitrate and nitrite reductase to convert inorganic nitrogen in wastewater to ammonia, which they can then mix with -ketoglutarate to produce amino acids for their own growth [17]. Phosphorus (P) is another macroelement required for the growth of microalgae and is used by microalgae for the phosphorylation of ADP and as the backbone of many biomolecules. Polyphosphate kinase and exopolyphosphatase in microalgae can catalyze the utilization of phosphorus in wastewater to generate polyphosphate to meet the demand of microalgae for phosphorus. Not only that, microalgae also have a certain ability to remove trace heavy metal elements in wastewater. It has been reported that microalgae have special short-chain polypeptides, such as phytochelatins and metallothionein, which have inherent properties to bind heavy metal ions and can also be used for heavy metal ion repair [16,18,19].

However, the excessive concentration of pollutants in some wastewater may affect the normal cultivation of microalgae. Therefore, before using the sewage, it is necessary to carry out relevant pretreatment processes on the sewage, such as AD, mMFCs, adsorption, etc., to adjust the concentration of each component in the sewage to achieve the most suitable conditions for microalgae cultivation.

In summary, the biological characteristics of microalgae have a good removal effect on many types of pollutants in wastewater. In the experiment of Li et al. in 2011 using chlorella to treat urban wastewater, it was found that the removal rates of ammonia, total nitrogen and total phosphorus reached 93.9%, 89.1% and 80.9%, respectively, and the effect was very good [20]. Therefore, if microalgae cultivation can utilize resources in wastewater on a large scale, then this technology has the opportunity to replace some technical processes in sewage treatment plants in the future and become a new type of sewage treatment process that can realize resource recycling.

4.2 Efficiency of microalgae CCU

Since photosynthesis is the primary mechanism used by microalgae to carry out the Bio-CCU process, increasing photosynthesis efficiency can help microalgae better capture CO_2 [21]. Secondly, the cultivation efficiency of microalgae is also closely related to the efficiency of CCU. Because the faster the growth and cultivation of microalgae, a large number of microalgae capable of carbon capture can be cultivated in a short period of time, thereby indirectly improving the efficiency of CCU.

In terms of pH value, the most suitable growth environment for microalgae is around 7-8.4 [22,23], because under this condition, most of the inorganic carbon can be directly obtained by microalgae as bicarbonate ions. However, in the specific cultivation process, the environmental pH value is also related to the composition of the nutrient solution and other factors, and with the continuous cultivation of microalgae, the pH value in the algae liquid will increase to a certain extent. Therefore, it is more complicated to maintain the pH value of the algae liquid environment, and the optimum pH of different algae is also slightly different, so the determination of the specific pH needs to be determined according to the specific situation.

Secondly, the temperature of the culture medium is also an important factor affecting the photosynthesis efficiency of microalgae. For most chlorella, the optimal growth temperature is between 15-30 Celsius degrees, and if the temperature is too high, the various enzymes in the algae will not be able to exert the maximum catalytic effect [24]. For example, in a recent experiment on the carbon dioxide capture efficiency of Spirulina, when the culture temperature increased from 23.8 to 33 °C, the capture efficiency increased from 25.5 to 51.3 g/m^2 /d [25]. However, when the temperature was subsequently increased to 38 °C, its efficiency decreased to 39.0 g/m^2 /d [25]. Therefore, when using microalgae to capture high-temperature CO_2 produced by factories, it is necessary to strictly control the temperature of CO_2 to avoid affecting the normal photosynthesis of microalgae due to excessive temperature.

The CO_2 concentration and gas composition in the industrial gas that needs to be captured also affects the efficiency of microalgae CCU. Some industrial waste gases contain excessive NO_X, SO_X and other gases that seriously affect the normal growth of microalgae [21]. Therefore, it is necessary to pre-treat the exhaust gas before capture, such as oxidizing toxic nitrogen oxides to more bioavailable NO_3^-. In addition, studies have shown that the optimal CO_2 concentration for microalgae growth is between 2% and 6%, while the CO_2 concentration in the flue gas that usually needs to be utilized is between 10% and 25% [26]. Directly passing high concentration of CO_2 gas into the microalgae culture tank will increase the acidity of the culture solution, thereby affecting the action of enzymes in the microalgae

4.3 Biomass produced by microalgae

According to research, 1 kg of microalgae biomass is capable of sequestering 1.83 kg of CO_2 in the environment [27]. Meanwhile, the biomass obtained by CO_2 sequestration can be utilized by converting into liquid and gaseous fuels. Therefore, microalgae are one of the possible pathways to achieve negative carbon emissions [14]. The photosynthesis products of microalgae contain different kinds of biomass, such as lipids, proteins and so on. The biomass can be processed into higher value usable products. While improving the material utilization rate, it brings certain economic benefits to microalgae carbon capture.

For example, the lipids in microalgae include a large number of fatty acid molecules, and these fatty acid molecules can be extracted as the basic material of nutrition [21]. In addition to lipids, microalgal biomass also contains liquid biofuels that can be utilized, usually in the form of carbohydrate derivatives. This form of biomass can be converted into high-energy liquid biofuels such as bioethanol and biobutanol after fermentation and other processes, and then replace part of the use of fossil fuels [14]. In addition, other biomass such as amino acids, peptides, and proteins are also of considerable utility value as food or feed supplements. A recent study found that peptides extracted from microalgal biomass have certain antioxidant and antibacterial properties, which can be utilized in industries such as pharmaceuticals and cosmetics production [21].

5 Conclusion

Under the general trend that the world is committed to the goal of carbon neutrality, the current power consumption and carbon emissions of most sewage treatment plants do not meet the requirements. The combination of sewage treatment and carbon capture technology is a good way to solve this problem. This paper lists three representative technologies in this field in recent years: MES, Microalgae cultivation, Constructed wetlands, and briefly summarizes the basic principles, advantages and research status of these three technologies in recent years. The research and development of these technologies for sewage treatment or carbon capture alone has been developed for a long time, but the research on the combination of sewage treatment and CCU has gradually increased in recent years. Therefore, these technologies are still a long way from industrial application, and there are still many problems to be solved, For example, reducing the impact of high-concentration pollutants in sewage on the biological function of microalgae, reducing the harvesting cost of microalgae biomass, and improving the product selectivity of microbial electrosynthesis, etc. In addition, due to the different actual conditions of different companies and different regions, the most suitable technologies are also different. For example, constructed wetland technology requires the use of a large amount of land, so countries or regions with little free land, such as China, may not be suitable. Therefore, exploring the selectivity of technology in different industries and regions is also the focus of the next research. Still, the concept of combining wastewater treatment and carbon capture holds great promise, and research on technologies related to this concept has grown in recent years. If these technologies can be widely used in the industry in the future, it can completely change the current high carbon emission status of the sewage treatment industry and provide great help to achieve global carbon neutrality.

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