Proceedings of the 4th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/58/20240715

Application and effect evaluation of membrane bioreactor technology in municipal wastewater treatment

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Abstract. Due to the increasing amount of urban sewage and improved standards in sewage discharge, simple traditional biological sewage treatment fails to meet the needs of municipal sewage treatment. Therefore, to treat wastewater more efficiently, the process of combining biofilm technology with traditional biological wastewater treatment appeared. This paper analyzes the advantages and problems of the combined processes of membrane separation technology and traditional biological sewage treatment technology from and perspective of complementary processes, and puts forward relevant measures to alleviate membrane fouling. The study found that Membrane Bioreactor (MBR) technology occupies a small area, and has a better sewage effluent quality and strong stability, also the sludge output is low. Anaerobic Membrane Bioreactor (AnMBR) technology can increase the effectiveness of removing organic matter and enable resource reuse, which satisfies the demand for low energy consumption. Membrane Aeration Bioreactor (MABR) technology involves bubble-free aeration that greatly improves the quality of sewage effluent, and the production of sludge in MABR technology decreases. Anaerobic ammonium nitrogen membrane bioreactor technology can enhance the efficiency of Anammox bacteria, and the energy consumption and economic cost of this technology are low. Although these membrane combination processes can effectively treat sewage, they can easily be limited by factors such as temperature, microbial communities, and membrane fouling. This paper provides guiding opinions for decision makers in the field of urban sewage treatment so that they can apply appropriate sewage treatment technology to local municipal sewage treatment, promoting the sustainable development of sewage treatment.

Keywords: Municipal Sewage Treatment, Membrane Bioreactor, Membrane Fouling.

1. Introduction

With the increasing scale of urbanization and the increase of urban population, the discharge of urban sewage has increased dramatically. There are suspended solids, organic and inorganic pollutants, such as nitrogen-containing pollutants and ammonia-pollutants in urban sewage, which cause eutrophication that affects the urban ecological environment. Such substances can enter the food chain through aquatic animals, endangering human health. What's more, with the improvement of urban living standards and the development of technology, the discharge standards of sewage have gradually increased. People's expectations do not stop at simple sewage treatment but also pay more attention to higher levels involving the reuse of waste after sewage treatment and sustainable development of energy consumption.

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According to the data of the '2021Urban and Rural Construction Statistical Yearbook' from the Ministry of Housing and Urban-Rural Development of the People's Republic of China [1], China's sewage treatment plants have reached 2827, and the daily urban sewage treatment capacity has reached 210 million cubic meters by the end of 2021. The treatment rate has reached 97.89%. However, urban sewage treatment still faces challenges in terms of technology, economics, and practical implementation. With the improvement of relevant standards for urban sewage discharge, traditional sewage technologies, such as anaerobic or aerobic biological treatment technologies, have failed to meet the sewage treatment needs for simultaneously removing organic matter and nitrogen phosphorus compounds contained in urban sewage. Due to the large population in urban areas and urbanization, the amount of urban sewage is huge, but the Chemical Oxygen Demand (COD) concentration of sewage is low, and the temperature of sewage is also low [2]. In this case, the traditional anaerobic biological treatment technology needs to shorten the Hydraulic Retention Time (HRT) to increase the organic load when treating urban sewage [2]. However, this practice will cause the loss of the total amount of anaerobic microorganisms and reduce the efficiency of methane production, thus limiting the application of traditional anaerobic biological treatment technology.

To deal with various problems faced by traditional biological sewage treatment technology in the treatment of urban sewage, biofilm technology has been applied to the field of sewage treatment because of its unique characteristics. Combining biofilm technology with different traditional biological sewage treatment methods to form membrane bioreactor technology can effectively solve the problems of poor effluent quality, high total nitrogen and total phosphorus content, and high COD concentration.

This paper aims to explore the application potential of the combination of traditional sewage biological treatment technology and membrane bioreactor processes in urban sewage treatment. This paper also analyzes the role of this technology in improving the efficiency of sewage treatment and reducing the environmental impact. Analyzing the advantages and problems of the membrane bioreactor process can provide insightful details for decision makers and researchers in the field of urban sewage treatment to promote more sustainable and efficient wastewater treatment solutions.

2. Biofilm

Biofilm is a condensed phase with selective permeability. The membrane can allow macromolecular proteins, solids, suspended solids, and other substances in the fluid to pass through the membrane or intercept those substances to achieve the effect of filtering and separating the substances in the fluid [3].

2.1. Principle of membrane separation technology

Membrane separation technology is a high-tech technology that combines physical, chemical, and biological disciplines. When a driving force is applied on both sides of the fluid, the membrane separation technology can be applied to separate the macromolecular substances and small molecular substances in the fluid through the selective permeability of the membrane [4].

The selective permeability of membranes can not only be used in material separation processes such as liquid purification and gas filtration but also has a wide range of applications in sewage treatment. Through this technology, sewage can be efficiently purified to obtain purer sewage [4].

2.2. Membrane fouling

Membrane fouling is a serious problem faced by membrane separation technology in sewage treatment. Membrane fouling is influenced by multiple factors, which are mainly caused by the physical characteristics of the membrane itself, the characteristics of pollutants in the sewage, and the equipment settings of membrane bioreaction technology [5]. Due to the characteristics of biofilm materials, chargeability and pore size of biofilm, impurities in sewage are difficult to decompose after a long-term sewage treatment process, and thus gradually accumulate on the surface of biofilm. This will lead to the blockage of the pore, which in turn will reduce the selective permeability of the membrane, and finally lead to the reduction of sewage treatment capacity and sewage treatment efficiency [6]. The roughness of the membrane and the pore size of the membrane differ from the materials selected for the membrane

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and the performance of the membrane surface. Affected by the membrane pore size, the particles larger than the membrane pore size in the sewage will accumulate because they fail to pass through the membrane surface, and the particles smaller than the membrane pore size will also accumulate in the pores of the membrane to form a filter cake layer. The microbial colony, salt concentration, particle size, and pH value in the sewage will affect the protein solubility of the membrane. The sludge composition in the sewage, the viscosity of the sludge, and the temperature of the sewage will affect the permeability and separation characteristics of the membrane. In addition, the operating pressure of the membrane bioreactor system, the effluent flow rate of the membrane, and the flow rate of feed liquid also have a direct impact on membrane fouling [6].

Therefore, a pressing issue in membrane bioreactor technology is how to increase the service life of the membrane and how to address the issue of membrane fouling.

3. Types of membrane bioreactor technology

Membrane bioreactor technology is a revolutionary method that combines membrane separation and traditional biological sewage treatment. Combining membrane-related technologies such as membrane separation with traditional sewage treatment methods can maximize the benefits of both technologies while compensating for their weaknesses. This comprehensive application has enabled a more efficient and high-quality municipal sewage treatment.

3.1. MBR

MBR technology is a novel approach that combines membrane separation with the classic activated sludge process. Due to the improvement of sewage discharge standards and the increase in urbanization scale, the available land area in cities has decreased. The MBR process has been more and more widely used in municipal sewage treatment because of its small footprint, improved effluent quality, and strong stability.

In traditional sewage biological treatment technology, when the muddy water is discharged into the secondary settling tank, the separation of the muddy water depends on the gravity of the sludge and the sedimentation performance of the sludge. The better the settling performance of activated sludge, the more efficient the sludge-water separation efficiency can be achieved. The sedimentation performance of sludge is related to the actual operation of the aeration tank, so the operating conditions of the aeration tank limit the scope of application of traditional sewage biological treatment technology. Besides, during the practice of traditional sewage biological treatment technology, sludge bulking will occur, increasing suspended solids in the effluent [6].

The MBR membrane bioreactor process combines high-efficiency membrane separation technology with traditional sewage treatment methods so that it no longer relies on gravity and sedimentation to separate muddy water. This combination effectively improves the efficiency of mud-water separation, and no longer needs to build a secondary settling tank at the same time. Using biofilm technology, most bacteria and viruses can be filtered, and this membrane can effectively resist sludge bulking, thereby improving the quality of effluent water. What's more, the MBR process can reduce the F/M ratio, thus reducing sludge production. Overall, by combining the membrane separation technology with the traditional activated sludge method, the MBR process can effectively solve some problems in the traditional method.

However, MBR technology also has shortcomings. In terms of economy, the manufacturing price of membrane materials and membrane components is relatively high. The membrane needs to be cleaned after a period of use to remove pollutants on the biofilm that affect the membrane flux and other properties. The cost of cleaning and reusing is also high. In terms of technical process, the manufacturing process of the membrane is relatively fine and has high requirements for the process. Influenced by membrane fouling, the attenuation of biofilm characteristics such as membrane flux will affect the quality of the membrane and the process operation mode, resulting in the need for frequent replacement of the biofilm after 5-10 years of use [7]. In terms of energy consumption, the suction water discharge

DOI: 10.54254/2755-2721/58/20240715

method of MBR technology, biofilm cleaning, and high-power sludge return all consume more energy [7].

3.2. AnMBR

AnMBR technology refers to a sewage treatment technology that combines anaerobic biological treatment technology with membrane separation. Anaerobic biological treatment technology is one of the most promising technologies in urban sewage treatment. Due to the large amount of municipal sewage, the COD concentration and the temperature of the sewage are low, anaerobic biological treatment technology needs to increase the organic load by shortening the HRT [2]. However, shortening the HRT will result in a slower rate of anaerobic sludge proliferation, resulting in increased sludge loss [2]. This will lead to shorter solid residence time, insufficient total amount of anaerobic microorganisms, and reduced methane production efficiency, which severely limits the application of anaerobic biological treatment technology in urban sewage treatment. Studies have shown that even if the temperature of municipal sewage is raised to medium temperature, the efficiency of methane production is still low [8]. AnMBR technology combines membrane separation technology and anaerobic biological treatment technology, making full use of the selective permeability characteristics of the membrane and the retention characteristics of the membrane module. This combination helps to solve the situation of serious microbial loss and retains anaerobic microorganisms to a higher degree. AnMBR technology can completely separate HRT and SRT, thereby improving the degradation and removal efficiency of organic matter [8]. AnMBR technology can not only improve the removal efficiency of organic matter but also convert organic matter into methane to generate high-quality biogas [9]. Besides, the actual operation of AnMBR technology requires low energy consumption and can realize resource recovery, which is helpful in achieving the sustainable development goal of urban sewage treatment.

The disadvantage of AnMBR technology is that the practical application of this is limited by various factors. In practical applications, AnMBR technology needs to rely on the role of methanogens [10]. However, municipal wastewater contains sulfate, which may trigger conflicts between sulfate-reducing bacteria and methanogens. This conflict can lead to inefficient methanogens and low methane production. In addition, the presence of sulfate-reducing bacteria can trigger the generation of H2S, which in turn affects biogas production and composition. Also, the deposition of sludge and the adsorption of organic matter on the surface of the membrane can cause membrane fouling problems [10]. This kind of problem will reduce the membrane flux, affect the selective permeability of the membrane, and thus affect the efficiency of sewage treatment.

3.3. MABR

MABR technology is a new sewage treatment technology combining traditional biofilm water treatment technology and membrane separation technology. The MABR process uses a combination of new breathable membrane materials and biological membranes. In this process, the biofilm is attached to the outside of the membrane material, and oxygen is transported from the outside to the inside through the membrane material to supply oxygen to the biofilm and realize bubble-free aeration [11]. The heterogeneous mass transfer characteristics of oxygen and substrate in the MABR biofilm system enable the system to form a unique hierarchical structure of microbial communities, which enables a variety of microorganisms to cooperate to achieve efficient sewage purification [12]. In this system, the biofilm is fully in contact with the sewage, the oxygen utilization rate is high, and the sludge production is extremely low. Pollutants such as organic matter, nitrogen, and phosphorus in sewage are transferred to the biofilm under the action of concentration gradient and hydraulic disturbance and are oxidized and decomposed by microorganisms, thereby realizing sewage purification [12]. Although the bubble-free aeration in MABR technology is its technical advantage and can improve the utilization rate of oxygen, it may cause uneven distribution of oxygen pressure in the biofilm, which will lead to insufficient oxygen supply in some areas, affecting the sewage treatment capacity and effect [12]. Also, the application of MABR technology will be affected and limited by temperature. Since the technology needs to be coupled with the activated sludge process, low water temperature may affect the denitrification activity of the activated sludge, thereby affecting the removal effect of total phosphorus in the effluent [11]. Besides, since MABR technology involves the use of membranes, various substances such as organic matter in urban sewage may reduce the activity of biofilms and even cause membrane fouling, affecting the adsorption and selective permeability of the membranes.

3.4. Anaerobic ammonium nitrogen membrane bioreactor

Anaerobic ammonium nitrogen technology is one of the methods of sewage treatment. It has a good prospect for low-carbon and sustainable economic development because it does not require the addition of organic carbon sources and aeration. The technical principle is to add Anammox bacteria under anaerobic conditions, which directly converts nitrogen-containing compounds in sewage into nitrogen [13]. However, Anammox bacteria are affected by many factors such as temperature, light, dissolved oxygen concentration, etc., so their stability is subpar. More, importantly, the enrichment and growth rate of Anammox bacteria is relatively slow, which leads to many limitations in the application of anaerobic ammonium nitrogen technology alone [13]. By combining membrane technology with anaerobic ammonium nitrogen technology, the enrichment characteristics of biofilm to bacteria can be fully utilized, and at the same time, the advantages of efficient denitrification, low economy, and low energy consumption of anaerobic ammonium nitrogen technology can also be fully utilized to form a technical win-win situation.

However, it is worth noting that the combination of these two technologies also faces some challenges. The impact of Anammox bacteria on biofilm will cause membrane fouling, which will seriously limit the efficiency and ability of this technology to treat sewage, and affect the long-term stability of sewage treatment equipment [13]. Moreover, the cleaning, renewal, and reuse of biofilms also involve higher costs and higher energy consumption.

In summary, although the performance of the technology can be optimized by combining membrane technology with anaerobic ammonium nitrogen technology, problems such as membrane fouling still need to be overcome to realize the comprehensive development and application of sewage treatment technology.

4. Membrane fouling control

Although the above-mentioned traditional biological sewage treatment technologies can better exert sewage treatment capacity and efficiency after being combined with membrane technology, all combined technologies have produced unavoidable membrane fouling problems. How to solve the problem of membrane fouling with low energy consumption and low economy has become the primary problem faced by biofilm wastewater treatment technology today. The measures to control membrane fouling are mainly solved from the relevant factors affecting membrane fouling.

4.1. Optimizing biofilm properties

The membrane's pore size, substance, charge, hydrophilicity, and hydrophobicity are the primary factors that determine the biofilm's properties. The pore size of the membrane is directly related to the roughness of membrane and the permeability of membrane. Generally, the larger the pore size of membrane, the higher the roughness of membrane is [5]. When the roughness of membrane is higher, it is easier for the sediment to accumulate on the surface of membrane and then form a denser filter cake layer, affecting the permeability of membrane. However, if the pore size of membrane is small, the permeability of the membrane will also reduce due to the increase in filtration resistance. Therefore, to prolong the service life of membrane and control the degree of membrane pollution, it is necessary to select the largest possible membrane pore size based on the size of the particles in the sewage to be treated. The choice of membrane material will also affect the membrane fouling. Choosing membranes with large membrane flux, strong anti-pollution ability, and easy cleaning is needed in the selection of membrane materials. Most of the colloidal particles in sewage are negatively charged. In order to lessen the pollution brought on by colloidal particles adhering to the membrane's surface, the membrane material with negative potential should be selected based on the principle of same-sex repulsion. The main pollutants in the early stage of membrane fouling are hydrophilic organic matter, while the main pollutants in the later stage of membrane fouling are hydrophobic organic matter [3]. Therefore, membrane fouling can be alleviated by changing the hydrophilicity and hydrophobicity of the membrane by adding hydrophilic substances on the membrane surface, ultraviolet irradiation, or surface grafting [5].

4.2. Optimizing the operating parameters of the membrane reactor

The parameters involved in the sewage treatment process technology include aeration, temperature, HRT, and Sludge Retention Time (SRT). Membrane fouling can be effectively delayed by optimizing the parameters of the membrane reactor. Aeration can generate shear force, and the scouring force can be adjusted by the intensity of aeration, thereby reducing the sediment on the membrane surface. The length of HRT and SRT will affect Mixed Liquor Suspended Solids (MLSS) and Extracellular Polymeric Substances (EPS). In the case of insufficient HRT time, microorganisms will metabolize and produce more EPS and Soluble Microbial Products (SMP) [5]. EPS and SMP will increase the filtration resistance of sewage and accelerate membrane fouling. In AnMBR technology, the activity of anaerobic microorganisms is greatly affected by temperature. A suitable temperature can keep the microorganisms active and remove organic matter more effectively, while a low temperature will make the microorganisms metabolize to produce more EPS, which is harmful to the membrane fouling.

4.3. Optimizing the characteristics of the sludge mixture

The particle size, MLSS, and microorganisms in the sludge mixture are the factors affecting the membrane fouling. Adding different types of functional materials, such as adding adsorbent (Poly Aluminium Chloride) can directly adsorb sludge floc deposition [5], or adding non-absorptive particles (polyethylene terephthalate pellets) to fix free microorganisms, which can reduce the concentration of SMP, sludge in the sludge mixture and the EPS content of sludge, and thus increasing the service life of membrane [14]. Furthermore, the quorum sensing method can also be used to add extracts that can effectively inhibit the secretion of signal molecules from bacteria into the sewage treatment system to inhibit the formation of biofilms, thereby delaying the pollution of biofilms [15].

5. Conclusion

By analyzing the combination of traditional biological sewage treatment technology and membrane separation technology, this paper discusses the advantages and problems of the combined sewage treatment process and also analyzes the common problems faced by this combined process. This provides ideas for the development of urban sewage treatment in a more efficient, low-energy, and sustainable direction.

This paper found that membrane separation technology fully utilizes the physical characteristics of biological membranes, enabling them to play roles in filtration, transportation, and enrichment in sewage treatment. It makes up for the problems of difficult enrichment of microorganisms, long time-consuming, and insufficient separation of sludge and water in traditional biological sewage treatment methods. MBR technology occupies a small area, can improve the quality of sewage effluent, and has strong stability. Also, the sludge output is low, but there are problems with economic cost, process accuracy, and membrane fouling. AnMBR technology can improve the COD removal rate its energy consumption is low, and it can realize resource reuse, but there are problems such as the microbial communities being affected by sewage properties, temperature, and membrane fouling. The bubble-free aeration in MABR technology greatly improves the quality of sewage effluent and the sludge output is low, but there are problems of insufficient regional oxygen supply and membrane fouling Anaerobic ammonium nitrogen membrane bioreactor technology can enhance the efficiency of Anammox bacteria with low energy consumption and low economic cost, but there is a problem of membrane fouling. There are some methods to deal with membrane fouling. By optimizing the operating parameters, the pollutants deposited on the surface of the membrane can be washed away, and the increase of EPS and SMP produced by microbial metabolism on the filtration resistance can be alleviated. By adding auxiliary materials, it is beneficial to decompose the particle pollutants adsorbed on the membrane's surface. Moreover, according to the overall characteristics of sewage, the appropriate membrane pore size and membrane material can be selected, and the surface properties of the membrane can be adjusted.

In the case of good control of membrane fouling, the combination of membrane separation technology and traditional biological sewage treatment technology can better meet the standards and policies of municipal sewage treatment. With the continuous enrichment of process practice and the gradual resolution of problems, membrane bioreactor technology will be more widely used in municipal sewage treatment.

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