Biological Treatment of Industrial Wastewater

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Abstracts. The objective of this study is to explore in depth the biological treatment technologies for industrial wastewater and to analyze their application and development with the aim of improving the efficiency of industrial wastewater treatment, reducing costs, and minimizing the adverse effects on the environment. Specifically, it includes: systematically summarizing and comparing the current common biological treatment technologies for industrial wastewater, analyzing their advantages and disadvantages, scope of application, and effectiveness, in order to improve the understanding and control of the biological treatment process. Biofilm treatment technologies include fluidized bed biofilm reactor (FBBR), membrane biofilm reactor (MBfR), moving bed biofilm reactor (MBBR), and rotating biological contactor (RBC). Further research and innovation are needed to improve treatment efficiency, reduce energy consumption and anaerobic treatment, control membrane pollution and degrade difficult-to-biodegrade substances.

Keywords: Wastewater treatment, membrane bioreaction technology, analysis, reflection.

1. Introduction

With the rapid development of industrialization, industrial wastewater has become one of the main sources of pollution that seriously affects environmental quality and ecosystem stability. Industrial wastewater is characterized by complex content, many types of suspended solids and high concentration of organic pollutants, which will cause great damage to the ecological environment if not properly treated.

Although traditional physicochemical treatment methods can remove some of the pollutants, their high cost, high energy consumption, and the generation of waste residue limit their application in industrial wastewater treatment. Therefore, more and more attention has turned to the application of biological treatment technology. Biological treatment of industrial wastewater is an environmental protection technology that utilizes microorganisms to degrade organic pollutants, remove suspended matter and transform inorganic pollutants. Through biological treatment, the organic matter in industrial wastewater can be degraded by microorganisms into simpler substances, thus reducing the pollution of the environment. Biological treatment not only has lower cost and energy consumption, but also can reduce the generation of waste, in line with the requirements of sustainable development.

In recent years, with the development in the fields of biology, microbiology and bioengineering, industrial wastewater biological treatment technologies have been constantly innovated and improved. For example, the application of technologies such as activated sludge, biofilm, biosorption and plant wetlands has achieved remarkable results. However, due to the complexity and diversity of industrial wastewater, there may be differences in the applicability of different processes in treating industrial wastewater of different compositions. Therefore, the research and exploration of industrial wastewater biological treatment technologies are still of great significance.

This thesis aims to explore the application and development of industrial wastewater biological treatment technology, summarize the current common treatment processes, and propose applicable treatment methods according to the characteristics of wastewater. Through in-depth study of the advantages and disadvantages of different technologies and the scope of application, it will provide new ideas and methods for industrial wastewater treatment.

2. Characteristics and Composition of Industrial Wastewater

2.1. Industrial Wastewater

Industrial wastewater refers to the wastewater, sewage and waste liquid generated in the process of industrial production, which contains industrial production materials, intermediate products, products and pollutants generated, with complex composition, high concentration and pollution, variability, temperature changes and may contain special pollutants and other characteristics. Complex composition makes industrial wastewater does not have a clear classification, for example, according to the products of industrial enterprises and processing object classification, can be divided into metallurgical wastewater, paper wastewater, chemical wastewater, dyes wastewater, tannery wastewater, pesticide wastewater, textile printing and dyeing wastewater and so on. If the wastewater is categorized according to the main components of the pollutants contained in the wastewater, it can be divided into acidic wastewater, alkaline wastewater, cyanide-containing wastewater, chromium-containing wastewater, mercury-containing wastewater, phenol-containing wastewater, oil-containing wastewater, organophosphorus-containing wastewater, and so on. It needs to be categorized according to the actual situation. With the rapid development of industry, the type and quantity of wastewater has increased dramatically, and the pollution of water bodies has become increasingly common and severe, posing a threat to human health and safety. Industrial wastewater treatment is crucial for environmental protection, and its importance even exceeds that of municipal wastewater treatment. Although industrial wastewater treatment has begun since the end of the 19th century and has been subjected to a large number of experiments and practices in the following decades, there are still some technical problems that have not been fully solved due to the complexity and variability of industrial wastewater compositions. This also makes industrial wastewater treatment have different characteristics and challenges compared to municipal wastewater treatment technologies.

The composition of industrial wastewater is diverse, including a variety of organic, inorganic, suspended, heavy metals and other chemicals. In general, industrial wastewater may contain organic constituents including petroleum-based substances, solvents, oils and fats, phenolic compounds, fatty acids, etc. Inorganic constituents generally include acids and alkalis, heavy metals (such as lead, mercury, cadmium, chromium, etc.), salts, ammonia and nitrogen, nitrites, nitrates and so on. Industrial wastewater from certain industries will also contain a large amount of suspended matter such as solid particles, soil, sand, gravel, fibers, suspended particles and so on. It is important to note that the composition of industrial wastewater varies from industry to industry. For example, industrial effluent from the chemical industry may contain more organic compounds; industrial effluent from the metal processing industry may contain higher concentrations of heavy metals; industrial effluent from the textile and dyeing industry may contain dyes and chemical additives, etc. Therefore, for specific industrial wastewater treatment, a detailed analysis and understanding of its specific composition is required to develop the appropriate treatment plan. The treatment process therefore needs to be adapted and optimized to the specific situation. Compared with municipal wastewater, industrial wastewater usually has a higher concentration and a more serious degree of pollution, which may contain a high concentration of organic matter, heavy metals, acids and alkalis, etc., posing a greater threat to the environment and ecosystem. At the same time, the composition and nature of industrial wastewater can change with time, production processes, product types and other factors, so treatment processes need to take this variability into account to ensure stable treatment results. Certain industrial processes may involve high or low temperature conditions, so the temperature of the resulting wastewater may be higher or lower than conventional wastewater treatment requirements. In addition, industrial wastewater may contain special pollutants, such as organic solvents, pesticides, and pharmaceutical residues, which pose potential risks to the ecological environment and require appropriate treatment methods. In summary, the characteristics of industrial wastewater require the use of appropriate treatment technologies and strategies to ensure efficient and safe treatment of industrial wastewater and to minimize its adverse effects on the environment.

3. Biological Treatment Technologies for Industrial Wastewater

3.1. Traditional Industrial Wastewater Treatment Methods

3.1.1 Physical treatment methods

Physical treatment processes play an important role in industrial wastewater treatment. Common physical treatment processes include grease traps, adsorption, high voltage electrical treatment, air flotation, filtration and centrifugal separation. These treatments are simple to operate, and therefore are widely used as pre-treatments in practical applications [1].

Oil separation is a method of separating grease and suspended matter from wastewater by gravity and surface tension. The method usually uses sedimentation tanks or oil-water separation equipment to float the grease on the surface of the water to form an oil layer, which is then scraped off by a device such as a scraper or inclined plate. Adsorption, on the other hand, utilizes an adsorbent (e.g., activated carbon) to adsorb organic material from the wastewater to the surface in order to remove organic pollutants.

High voltage electrical treatment is a method of treating suspended matter and ions in wastewater using a high voltage electric field. Through the action of the electric field, the charged particles will move toward the electrodes, gather on the electrodes, and can be separated from the solid-liquid by precipitation or filtration [2].

Air flotation is a physical treatment method that separates suspended solids by injecting fine bubbles into the wastewater, causing the suspended solids to agglomerate and form floating bubbles. It is usually used to remove small suspended solids and oil slicks. In the air flotation process, air is generally used as the bubble source. Floating bubbles are formed through the combination of air bubbles with suspended particles, which are less dense and can float on the surface of the liquid. Subsequently, a scraper device or cyclone can scrape or remove the floating bubbles and the suspended matter in them from the liquid surface, thus separating the solids from the liquid. Common types of air flotation equipment are air flotation tanks and air flotation settling tanks [3, 4].

Filtration is a common physical treatment method that utilizes filters or filter media to retain solid particles in wastewater. Filters can be selected from different types and sizes of filter media as needed, such as sand filters and activated carbon filters.

Centrifugal separation, on the other hand, utilizes centrifugal force to separate solid particles or suspended matter in wastewater through a centrifuge. The rotational speed of the centrifuge allows heavy particles to settle to the bottom of the centrifuge tube, while the clean liquid is thrown out.

These physical treatment processes are often used in combination in actual projects, and appropriate treatment methods are selected according to the characteristics of the wastewater and treatment requirements to achieve the desired treatment effect.

3.1.2 Chemical treatment methods

Traditional chemical treatment methods for industrial wastewater include neutralization, chemical precipitation, and oxidation reduction.

Neutralization is the process of adjusting the pH of wastewater by adding an acid or alkaline agent to bring it closer to neutral. Acid and alkali chemicals can react chemically with acidic or alkaline substances in the wastewater and neutralize them [5]. Commonly used neutralizing agents include sodium hydroxide and calcium hydroxide. Neutralization method can effectively remove the problem of too high or too low acidity and alkalinity in wastewater and improve the effectiveness of subsequent treatment steps. When the concentration of acid and alkali in wastewater reaches 3% to 5% or more, consideration should be given to whether recycling should be carried out, but if the concentration is less than 2% and recycling is uneconomical, neutralization should be used.

Chemical precipitation is a widely used method of industrial wastewater treatment, mainly for the presence of metal ions or phosphorus and other pollutants. The basic principle is to add specific chemicals to the wastewater, so that it reacts with the dissolved impurities in the water and produces insoluble salt precipitates, thus effectively reducing the content of dissolved impurities in the wastewater to achieve the effect of removal. The basic principle of chemical precipitation method for phosphorus removal is to form insoluble precipitates from phosphate and calcium, iron or aluminum salts by adding chemicals, and then remove the phosphate from the wastewater by solid-liquid separation method [6-8]. Commonly used precipitants include lime, aluminum sulfate, ferric trichloride, iron sulfate, ferrous sulfate, and ferric polyaluminum chloride. During neutralization and precipitation, phosphate competes with calcium, iron or aluminum ions for ligand groups and undergoes a chemical reaction and precipitates, achieving phosphorus removal. In terms of heavy metal removal, the more commonly used chemical precipitation methods include hydroxide precipitation and insoluble salt precipitation. Hydroxide precipitation, also known as neutralization precipitation, when alkali is added to heavy metal-containing wastewater, the metal cations are precipitated in the form of hydroxide or salt. Insoluble salt precipitation method is to use the precipitant and the metal ions in solution to form insoluble compounds to remove or recover the metal ions, including sulfide precipitation, carbonate precipitation, phosphate precipitation, barium salt precipitation method [9, 10].

Advanced oxidation technology is mainly divided into several categories such as Fenton and Fenton-like oxidation, photocatalytic oxidation, ozone oxidation, ultrasonic oxidation, wet oxidation and supercritical water oxidation. Fenton oxidation and wet air oxidation, which are more frequently used, are introduced here.

The Fenton method is a method that uses Fe^{2+} to catalyze the decomposition of H_2O_2 to produce -OH radicals under acidic conditions (pH 2-5) to degrade pollutants, which shows more obvious advantages when treating, for example, phenol and aniline compounds [11]. At the same time, the generated Fe^{3+} can also remove organic matter through coagulation. Therefore, in water treatment, Fenton reagent has both oxidizing and coagulating functions. In recent years, UV and visible light have been introduced into the Fenton system, and the use of other transition metals to replace Fe^{2+} has been investigated [12]. These innovations can significantly improve the oxidative degradation of organic matter in Fenton-like reaction systems, while reducing the amount of Fenton reagents required, thus reducing treatment costs. Therefore, these new research methods are collectively referred to as Fenton-like reactions.

Wet oxidation, also known as wet combustion, is a well-established method of treating highly concentrated organic wastewater. The basic principle is to pass air into the wastewater under high temperature and high pressure, so that the organic pollutants in the wastewater are oxidized and degraded. This process is divided into wet air oxidation and wet air-catalyzed oxidation according to whether or not a catalyst is added. Wet oxidation methods are carried out at high temperatures (about 150 °C to 325 °C) and high pressures (about 0.5 to 20 MPa), using oxygen or air as an oxidizing agent to oxidize dissolved or suspended organic matter or inorganic matter in the reduced state in the water, producing products such as carbon dioxide and water. [13] The wet air-catalyzed oxidation method involves the introduction of an appropriate catalyst into a conventional wet oxidation treatment process to achieve a complete oxidation reaction under milder reaction conditions and in a shorter period of time. This reduces the temperature and pressure required for the reaction, improves the oxidative decomposition capacity, accelerates the reaction rate, and shortens the residence time. At the same time, this improvement can also reduce equipment corrosion problems and reduce operating costs. This improvement makes the wet air catalytic oxidation technology more widely used [4, 13].

3.1.3 Traditional biological treatment methods

Biological treatment is one of the most commonly used methods for wastewater treatment at present, which is characterized by wide range of application, strong adaptability, economic efficiency and harmlessness. In general, the two commonly used biological methods are traditional activated sludge method and biological contact oxidation method. At present, the most commonly used traditional biological treatment method in industrial wastewater treatment is the activated sludge method. Activated sludge is a kind of aerobic biological treatment of sewage, which can remove dissolved and colloidal biochemical organic matter as well as suspended solids and some other substances that can be adsorbed by activated sludge from sewage, and also remove part of phosphorus and nitrogen. It has a high removal rate and is suitable for treating wastewater with high water quality requirements and relatively stable water quality [14].

3.2. Emerging Biological Treatment Technologies for Industrial Wastewater

3.2.1 Biofilm technology

Biofilm is considered to consist of an active population of single or mixed species of microorganisms that are attached to active or inactive surfaces in an irreversible manner [15]. Many domestic and international researchers have conducted a lot of research on biofilms and have achieved important results. Biofilm technology is an effective method applied to industrial wastewater treatment. It utilizes microorganisms to degrade and transform organic substances in wastewater by forming a film of microbial aggregates on a solid carrier or support material. Biofilm technology includes a variety of application forms, such as fluidized bed biofilm reactor (FBBR), membrane biofilm reactor (MBfR), moving bed biofilm reactor (MBBR), and rotating biological contactor (RBC) [16]. Fig. 1 is an overview of bacterial biofilm formation, factor affecting, and possible applications [17].

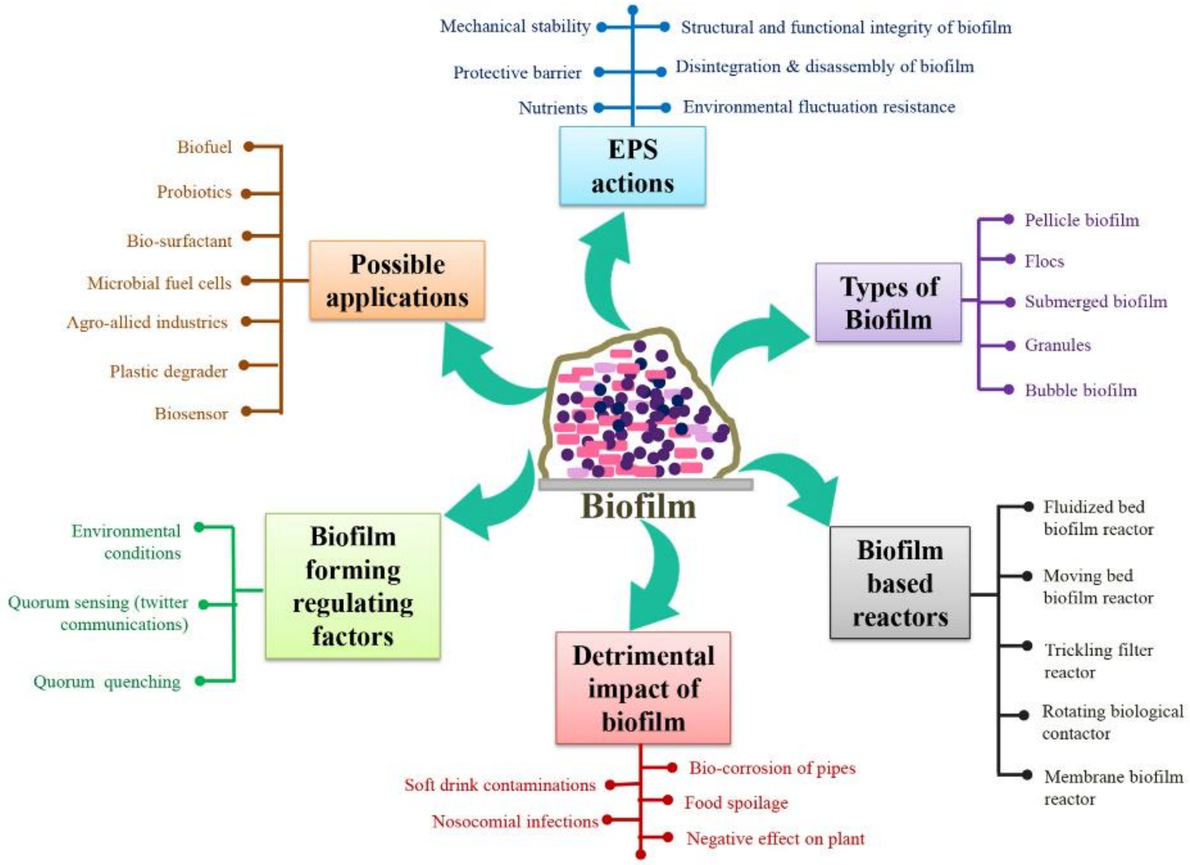

Fig. 1 An overview of bacterial biofilm formation, factor affecting, and possible applications.
https://link.springer.com/article/10.1007/s11274-023-03567-7

3.2.1 FBBR

This type of reactor is similar to a filled bed reactor in that small solid particles are moved continuously by hydraulic means. As the wastewater passes through the solid particle filled bed, a biofilm forms on the surface of these particles. In such a reactor, the solid particles are suspended at a sufficient velocity by the flow of fluid (gas or liquid) as if they were rotating in a pot of boiling water or a stirred tank.[16] Wastewater enters from the bottom of the packed bed and is passed through the bed by a rising flow of bubbles or gases, which suspends the packed particles and creates a fluidized state.

As the wastewater passes through the packed bed, microbial biofilms attach to the surface of the packing and utilize the organic matter in the wastewater for metabolism and degradation. The biofilm formed by microorganisms on the packing provides an efficient biological interface that promotes the transformation and removal of organic matter from the wastewater. At the same time, the fluidized state of the packing ensures adequate mixing and oxygen transfer, providing sufficient oxygen for the microorganisms to support their growth and metabolic activities.

3.2.2 MBBR

In MBBR, biofilms are formed on moving low-density plastic carriers or media. These carriers are moved within the reactor under aerobic and anaerobic conditions by means of aeration or mechanical agitators. Microorganisms grow as biofilms on the surface of MBBR carriers [16]. Carriers should have a density close to neutral buoyancy and are usually made of stable materials such as polyethylene or polypropylene. Some researchers have tried to optimize biofilm formation in MBBR using different carrier materials and modifications and after using polyurethane sponge as a carrier to treat synthetic wastewater in MBBR, it was found that an increase in the percentage of carrier filling was positively correlated with nitrogen deficiency and nitrification denitrification process. Physicochemical surface modification is also a method to improve MBBR biofilm formation, which can be achieved by introducing various chemical functional groups, using hybrid materials, polymer hybridization and coatings. Fig. 2 is schematic diagram of MBBR working principle.

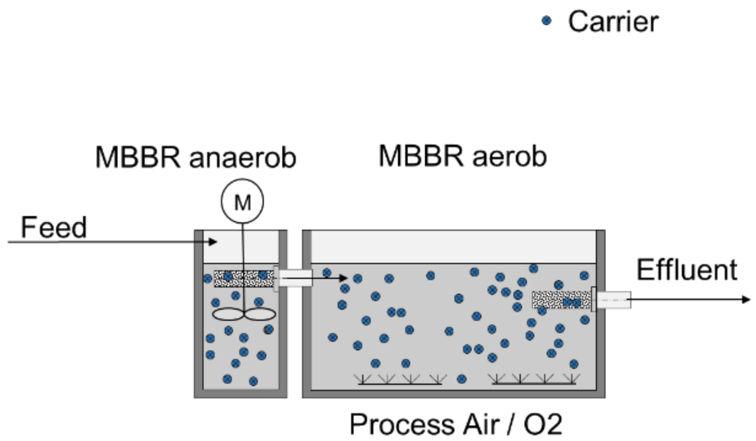

Fig. 2 Schematic diagram of MBBR working principle.
https://www.canadianbiomassmagazine.ca/application-of-the-mbbr-and-ifas-technology-in-biological-water-treatment-6376/

3.2.3 RBC

RBC is a biological treatment technology commonly used in wastewater treatment, which utilizes rotating discs to cultivate microbial biofilms to remove organic matter and other pollutants from wastewater through microbial attachment and metabolism. It utilizes rotating discs to cultivate microbial biofilms, which remove organic matter and other pollutants from wastewater through microbial attachment and metabolism. RBCs typically consist of a series of rotating discs arranged in parallel, which rotate on a horizontal axis, and the entire system is submerged in the wastewater. During rotation, wastewater is introduced by pumps or other means and evenly distributed across the rotating disks. The surface of the discs is covered with biofilms obtained from the wastewater, and these microbial films carry out their metabolic activities through the microorganisms attached to the surface of the discs. The microbial films degrade and oxidize the organic matter in the wastewater during the rolling and contacting process of the wastewater on the rotating discs. The organic matter in the wastewater is utilized by the microorganisms as an energy source, while the microorganisms also require oxygen for their metabolic processes. Therefore, in an RBC system, oxygen is supplied through the introduction of air or the provision of an aeration device. At the same time the rotation of the disk creates shear force which inhibits the overgrowth of biofilm and the excess sludge is transferred to the settling tank [18]. Fig. 3 is schematic diagram of RBC's working principle.

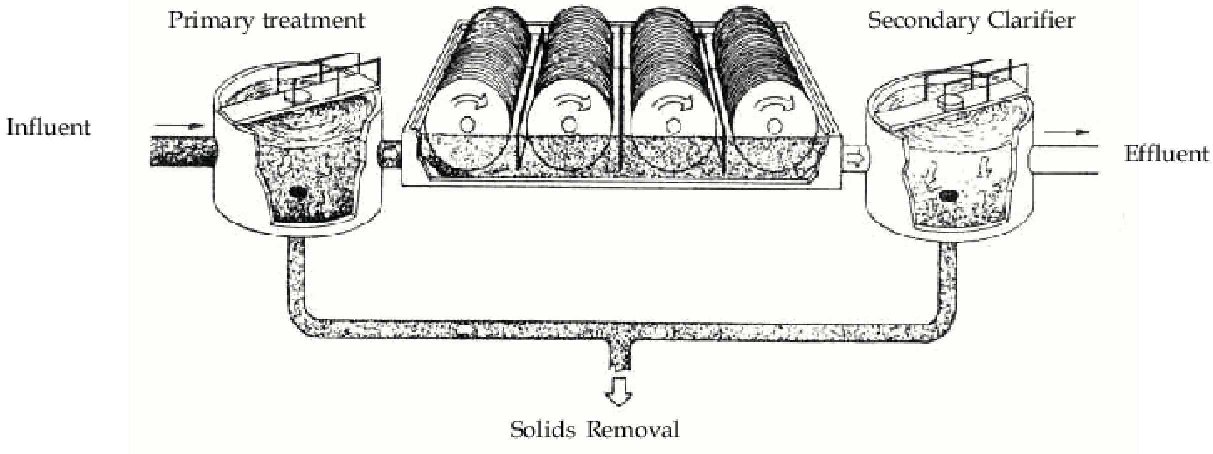

Fig. 3 Schematic diagram of RBC's working principle.
https://www.researchgate.net/figure/Rotating-Biological-Contactors_fig3_221911472

4. Challenges and Solutions

The presence of high concentrations and complex organics is one of the more difficult problems in industrial wastewater treatment. There is a wide range of industrial wastewater, including but not limited to wastewater generated from chemical, pharmaceutical, food processing and textile industries. These wastewaters contain a variety of organic compounds such as organic solvents, oils and fats, phenolics and heavy metal ions. Due to the high concentration and difficult degradation characteristics, a single biological treatment alone often fails to achieve the desired results [19]. This is because high concentrations of organic matter inhibit the growth and metabolic activities of microorganisms, resulting in inefficient or ineffective removal of organic matter by the biological treatment process. Meanwhile, certain complex organic matter has a complicated structure and is difficult to be degraded by microorganisms. In addition to this, biodegradation of toxic substances is equally difficult. There are two main challenges involved in the biodegradation of toxic substances: the structural complexity of toxic substances and the inhibition of microbial activity by toxic substances. First, the structural complexity of toxic substances makes them difficult to be degraded by microorganisms. These compounds may consist of multiple functional groups, making it more difficult to find the appropriate enzymes in the microbial metabolic pathway for degradation. In addition, some toxic substances are environmentally persistent, i.e. they are difficult to be completely degraded by organisms in nature. Secondly, toxic substances inhibit microbial activity. High concentrations of toxic substances can interfere with microbial growth and metabolic activity, leading to a decrease or even a complete cessation of degradation. Some toxicants may also cause damage to the genetic material of microorganisms, further slowing down the rate of degradation. To address these challenges, treatment is often required in conjunction with other means such as physicochemical methods.

The technical adaptability and stability of biological treatment is also a similar challenge, as industrial wastewater produced by different industries and processes has variability, including wastewater composition, concentration, pH, temperature, etc. Therefore, it is important to select biological treatment technologies that are suitable for the characteristics of specific industrial effluents. For example, industrial wastewater with high concentrations of organic matter can be treated with aerobic/anaerobic bioreactors (e.g., MBR, SBR, UASB, etc.); for wastewater containing heavy metals, a combination of biological and chemical methods may be required. Therefore, the characteristics and actual situation of industrial wastewater should be fully considered when selecting biological treatment technologies to ensure the adaptability of the technology.

Stability in the biological treatment of industrial wastewater is a key factor in ensuring continuous operation of the treatment system and stable removal of pollutants. However, the complexity, volatility and toxicity of industrial wastewater may negatively affect the biological treatment system, leading to a decrease in treatment capacity or even collapse. To improve the stability of the technology, operating conditions such as adjusting temperature, pH and aeration can be optimized to create suitable environmental conditions to promote microbial activity and stability. The establishment of a multi-species coexisting biological community is also effective, which can improve the system's ability to degrade different pollutants and anti-interference ability. The most important thing is to do a good job of process monitoring and control, regular monitoring of key parameters, timely adjustment of the treatment process, to avoid the impact of unexpected events on the system. Such as monitoring dissolved oxygen, COD in sewage, ammonia nitrogen and other indicators, and according to the monitoring results of the corresponding adjustment.

5. Conclusion

This thesis focuses on biological treatment technologies for industrial wastewater. Firstly, traditional physical and chemical treatment methods are introduced, and then biofilm treatment technologies such as FBBR, MBBR and RBC are emphasized. Compared with traditional treatment methods, biofilm treatment technology has some significant advantages. Biofilm technology can utilize microorganisms to degrade and transform pollutants, which is efficient, economical and environmentally friendly. In contrast, traditional treatment methods require large amounts of chemicals and energy consumption, and it is difficult to completely remove organic pollutants from wastewater. Biofilm treatment technologies such as FBBR, MBBR and RBC are widely used in the field of industrial wastewater treatment. These technologies utilize biofilm carriers to provide attachment surfaces that allow microorganisms to fully utilize the pollutants in organic wastewater for degradation. At the same time, these technologies have the advantages of simple operation, stable operation and small footprint. In the future, there are some challenges and directions for improvement in biological treatment technologies for industrial wastewater. For example, further research and innovation are needed to improve treatment efficiency, reduce energy consumption and anaerobic treatment, control membrane pollution and degrade difficult-to-biodegrade substances. In addition, combining other technologies to increase efficiency and dealing with the influence of multiple environmental factors are also the focus of future research. In the field of industrial wastewater treatment, biofilm treatment technology has a broad application prospect and development potential. Through continuous research and innovation, the efficiency of industrial wastewater treatment and the ability to remove specific pollutants can be further improved, and a more environmentally friendly, economic and sustainable wastewater treatment process can be realized, which will make a greater contribution to the protection of the environment and human health.

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