Study on the Application Strategy of Microbial Community Structure Optimization in Industrial Wastewater Treatment

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Abstract: Industrial wastewater is difficult to treat due to its complex composition. Conventional wastewater treatment methodologies are plagued by two primary issues: low efficiency and high cost. The microbial community degrades pollutants through metabolism, and its structural optimization is crucial to improve treatment efficiency and enhance system stability. In this paper, the diversity, dominance, and dynamic adaptability of microbial communities in industrial wastewater treatment are analyzed, and the effects of wastewater characteristics and process conditions on community structure are discussed. Additionally, it delineates an optimization strategy predicated on environmental regulation of nutrition, physical and chemical parameters, hydraulic conditions, and bioaugmentation functional flora screening, stress-tolerant flora domestication, and efficient strain enrichment. Finally, this study highlights issues in the current applications, such as instability, high costs, and ecological risks. It also explores future development directions that integrate bioinformatics and intelligent regulation, providing a reference for optimizing industrial wastewater biological treatment technology.

1. Introduction

1.1 The Present Situation and Challenges of Industrial Wastewater Treatment

Industrial wastewater is a general term for all kinds of sewage produced in the industrial production process. It has a wide range of sources and covers many industries, such as the chemical industry, metallurgy, printing and dyeing, and food processing. The composition of wastewater is intricate, often exhibiting elevated concentrations of organic matter, heavy metals such as chromium, lead, and mercury, as well as toxic and deleterious chemicals, including phenols, cyanide, antibiotics, high salt, and high ammonia nitrogen. If they are directly discharged without effective treatment, they will seriously pollute water, soil, and groundwater, threatening ecological balance and human health.

At present, the treatment of industrial wastewater is predominantly reliant upon physical methodologies, encompassing filtration and precipitation processes. In addition, chemical methods, including oxidation, neutralization, and biological methods such as activated sludge and biofilm, play a pivotal role in the treatment process. Although physical and chemical methods can quickly remove some pollutants, they have several drawbacks: high treatment costs, the potential for secondary pollution, such as chemical sludge, and limited degradation ability for complex organic matter [1].

Because of its low cost and environmental friendliness, biological methods are widely used. However, problems such as unstable treatment efficiency and weak impact resistance often occur because of the complexity, fluctuation, and toxicity of industrial wastewater. For example, high concentrations of toxic substances will inhibit microbial activity, and sudden changes in water quality and quantity will destroy the balance of flora, resulting in substandard effluent. These problems make it difficult to consider both efficiency and stability in industrial wastewater treatment.

1.2 The Role of Microorganisms in Industrial Wastewater Treatment

Microorganisms play a central role in the biological treatment of industrial wastewater. They transform and remove pollutants through their metabolic activities, making this approach a low-cost

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and sustainable method for pollution control.

From the principle of action, microorganisms can decompose organic substances such as starch, oil, and phenols in wastewater into harmless substances such as carbon dioxide and water through aerobic respiration and anaerobic fermentation. Moreover, some microorganisms can reduce heavy metal ions, such as hexavalent chromium, to low-toxic or non-toxic forms, such as trivalent chromium, by bio-transformation, or fix them by adsorption and accumulation. In addition, certain microorganisms can degrade synthetic pollutants like pesticides and dyes, breaking their chemical stability [2].

More importantly, microorganisms do not take effect alone in wastewater treatment, but play a role in the form of communities. Different kinds of microorganisms collaborate to make an influence. For example, aerobic bacteria are responsible for decomposing easily degradable organic matter, anaerobic bacteria are responsible for treating high-concentration organic wastewater, and producing methane. Nitrifying bacteria and denitrifying bacteria cooperate to remove nitrogen. The complementary functions of microorganisms in a community allow them to adapt to the complex environment of wastewater. This adaptation enhances their ability to degrade pollutants and improves their overall environmental resilience compared to a single strain. The collaborative behavior is essential for the stable operation of biological treatment systems.

1.3 Significance of Optimizing Microbial Community Structure

Optimizing the microbial community structure, that is, by adjusting the species composition, the proportion of dominant populations, and the interaction relationship in the community, enhances its pollutant degradation ability and environmental adaptability, which is of great practical significance for treating industrial wastewater.

Optimizing the community structure directly improves the treatment efficiency. By enhancing the dominant microbial flora with specific degradation functions—such as decolorizing bacteria that break down dyes and lipase-producing bacteria that decompose oils—we can effectively remove refractory pollutants from wastewater. This approach addresses the issue of incomplete degradation often encountered with traditional biological methods and leads to improved effluent quality [3].

Optimizing the microbial community structure enhances the impact resistance of the system. The water quality of industrial wastewater, such as pH, toxic substance concentration, and water quantity, often fluctuates with production. A stable community structure can be achieved through functional redundancy among species. In other words, many microorganisms have similar metabolic functions. When some plant species are inhibited, other species can compensate for the functional gap over time to prevent the collapse of the treatment system.

The optimization is conducive to reducing the processing cost. By directionally regulating the flora structure, the use of chemical agents such as oxidants and flocculants can be reduced, and energy consumption, such as aeration intensity, can be reduced. At the same time, the reduction in excess sludge output leads to a decrease in operating costs. The optimized community will utilize nutrients in wastewater more effectively, decrease the need for external nutrient supplements, and achieve further energy savings and reduced consumption, aligning with environmental protection trends.

2. Characteristics and Influencing Factors of Microbial Community Structure in Industrial Wastewater Treatment

2.1 Basic Characteristics of Microbial Community Structure

The microbial community structure in industrial wastewater treatment systems exhibits three noteworthy characteristics. Firstly, the community is characterized by its biodiversity, encompassing a diverse array of microorganisms, including bacteria, fungi, and archaea. This ecological diversity fosters a high level of species richness and uniform distribution. The stable operation of the system is predicated on diversity, and the division of labor among different microorganisms is complementary. This division of labor enables the microorganisms to deal with complex pollutants in wastewater and avoid system function collapse when a single species is inhibited.

Second, it has the dominant function of the dominant population. For example, when treating phenol-containing wastewater, bacteria producing phenol oxidase often become the dominant population.

Third, the community is characterized by its dynamic adaptability, and the community structure will be adjusted with environmental changes. As the wastewater quality and treatment conditions change, the dominant population may change and the weak population may proliferate. Hence, the system functions through self-regulation, allowing the community to sustain a certain treatment capacity amidst the fluctuating environment of industrial wastewater.

2.2 Primary Factors Affecting Microbial Community Structure

Many factors influence microbial community structure, and they can be divided into three categories. First of all, it is affected by the characteristics of wastewater itself, and the type and concentration of pollutants are the most important. High concentrations of organic matter can promote heterotrophic bacteria reproduction, while heavy metals will inhibit sensitive microorganisms and screen out drug-resistant bacteria. Moreover, fluctuations in water quality, such as sudden changes in pH and rising salinity, will directly affect microbial activity and lead to rapid changes in community composition. Second, the environmental conditions of the treatment process affect the microbial community structure, and the dissolved oxygen level determines the microbial community type. An aerobic environment is conducive to the growth of aerobic bacteria, while an anaerobic environment is suitable for the reproduction of anaerobic bacteria. Furthermore, the proportion of nutrients is also very vital. The imbalance of carbon, nitrogen, and phosphorus will limit the metabolism of specific microorganisms [4]. For example, nitrogen deficiency will inhibit the proliferation of nitrifying bacteria; Excessive hydraulic retention time or load will wash away some microorganisms and change the species ratio of the community. Finally, the microbial community structure is influenced by external factors, including toxic substances like antibiotics and fungicides in wastewater, which can directly harm or inhibit certain microorganisms. Additionally, the introduction of foreign microorganisms can occupy the habitat of local flora, disrupting the balance of the original community.

3. Optimization Strategy of Microbial Community Structure Based on Environmental Regulation

3.1 Regulating Nutritional Conditions to Optimize Community Structure

Nutritional conditions are the basis of microbial growth and metabolism, and regulating nutrition can guide the community structure to become highly efficient in degradation. Its core is to balance the ratio of carbon, nitrogen, and phosphorus. Different pollutants require functional flora with specific nutritional needs. For instance, when treating nitrogen-rich wastewater, it is crucial to increase the nitrogen ratio to encourage the growth of nitrifying and denitrifying bacteria. For another example, when treating high-carbon organic wastewater, it is necessary to increase the supply of carbon sources to meet the metabolic needs of heterotrophic bacteria. In practice, the proportion can be adjusted by adding carbon source, nitrogen source, and phosphorus source to avoid the inhibition of some functional flora due to nutritional imbalance.

In addition, it is important to supplement micronutrients. Iron, magnesium, and zinc are the components of microbial enzymes. Appropriate addition can enhance enzyme activity and promote the proliferation of flora. By carefully regulating nutrition, the target beneficial flora can enhance their competitive advantage and improve the efficiency of degrading specific pollutants within the community.

3.2 Regulation of Physical and Chemical Parameters to Optimize Community Structure

Physicochemical parameters directly affect the living environment of microorganisms. Reasonable regulation is conducive to screening out dominant bacteria and maintaining their activity. Dissolved oxygen is a critical parameter in this context. In the aerobic process, it is imperative to maintain elevated dissolved oxygen levels, promote the proliferation of aerobic bacteria, and enhance the oxidative decomposition of organic matter. The anaerobic process requires precise oxygen control to create an optimal environment for anaerobic bacteria, such as methanogens, thereby enhancing the treatment efficiency of high-concentration organic wastewater [5].

It is imperative to regulate the pH value within the optimal range for the majority of microorganisms to circumvent deleterious effects on the cell membrane and enzyme structure, which can be caused by excessive acid or alkali. The addition of acid-base regulators can stabilize the pH. Additionally, the temperature also needs to be adapted to the characteristics of the flora. The mesophilic bacteria have the highest activity at mild temperatures, and the thermophilic bacteria are suitable for higher temperature environments. Therefore, researchers promote the metabolism of the target flora and inhibit the temperature-resistant microorganisms through temperature control, thereby optimizing the community structure.

3.3 Regulating Hydraulic Conditions to Optimize Community Structure

Hydraulic conditions indirectly change community composition by affecting the residence time and living space of microorganisms. Optimizing the hydraulic retention time is essential, and its adjustment must be made based on the complexity of the pollutant degradation process. In the context of readily biodegradable organic matter, the retention time can be reduced, thereby mitigating the proliferation of ineffective bacteria. In contrast, the treatment of refractory pollutants requires an extended time for functional flora to complete metabolism.

It is imperative to regulate the hydraulic impact to avert the abrupt escalation in water quantity over a brief period, as this can result in the displacement of a substantial number of microorganisms. It is suggested that the fluctuation of water quantity should be buffered by setting the regulating tank. Organic load should also be controlled reasonably, because excessive load will lead to imbalance of microbial metabolism, and dominant flora will be inhibited due to overnutrition or accumulated toxicity; If the load is too low, the number of flora will decrease due to insufficient nutrition. By stabilizing hydraulic conditions, the dominant flora in the community will consistently maintain a leading role, ensuring structural stability and treatment efficiency.

4. Optimization Strategy of Microbial Community Structure Based on Bioaugmentation

4.1 Screening and Inoculation of Functional Flora for Nutritional Needs

The fundamental objective of screening and inoculating functional flora to address nutritional deficiencies in industrial wastewater treatment systems is to enhance the utilization capacity of nutrients, thereby optimizing the nutritional metabolism balance within the community through targeted supplementation of flora. Industrial wastewater typically contains an imbalanced ratio of nutrients [6]. For example, some chemical wastewater contains abundant carbon sources but lacks nitrogen and phosphorus. For another example, in food wastewater, nitrogen and phosphorus are in surplus. Still, specific carbon sources (such as cellulose) are difficult to utilize, which leads to an insufficient number of related functional flora in the original community and limited treatment efficiency.

When screening the flora, we can take samples from activated sludge, soil, or water that has treated similar wastewater for an extended period and cultivate them using a selective medium. For example, in wastewater deficient in nitrogen, a culture medium containing only ammonium salt is utilized to screen for bacteria that can efficiently utilize nitrogen. In wastewater containing a refractory carbon source, this source serves as the sole energy source for enriching microorganisms capable of decomposing it. The screened functional flora needs an adaptive culture to ensure its survival and function in the target wastewater environment.

During inoculation, the cultivated flora is introduced into the treatment system with the objective of supplementing the deficient or impaired nutritional metabolism function within the community. For example, inoculating phosphorus-accumulating bacteria into phosphorus-deficient wastewater enhances the community's ability to absorb and transform phosphorus. Additionally, inoculating the compound flora that can efficiently transform carbon and nitrogen into the system with an unbalanced carbon-nitrogen ratio promotes the synergistic utilization of nutrients. By using these methods, the community will make full use of all nutrients in wastewater, avoid the decline of flora activity caused by nutritional restrictions, and then optimize the function and stability of the community structure.

4.2 Domestication and Introduction of Stress-tolerant Flora for Specific Environment

The specific environment of industrial wastewater (such as high salt, high toxicity, extreme pH value, high temperature, etc.) often inhibits the activity of ordinary microorganisms, resulting in a single community structure and weakened functions. The domestication and introduction of stress-tolerant flora in this environment aim to enhance the community's adaptability to harsh conditions and ensure its stable operation.

To domesticate the stress-tolerant flora, it is suggested to adopt the "gradient stress method": to obtain the original flora from natural extreme environments (such as salt lakes, acid-base mines) or water bodies that have been polluted for the same reason for a long time. Subsequently, the intensity of environmental stress is gradually increased in the laboratory. For example, when treating high-salt wastewater, the flora is initially cultured in a low-salt medium. The salt concentration is then increased weekly until the flora can metabolize normally in the target wastewater. When treating wastewater with high concentrations of toxins, gradually increase the levels of toxins and select for flora that can tolerate and degrade them. The process induces the flora to produce adaptive metabolic mechanisms, such as the synthesis of salt-tolerant proteins and detoxification enzymes.

The introduction of acclimated, stress-tolerant flora has been demonstrated to be a beneficial strategy for addressing the functional deficiencies of the original community in harsh environments. For example, introducing acid-resistant bacteria into printing and dyeing wastewater with low pH values helps avoid inactivation of ordinary microorganisms due to acid stress. Similarly, introducing heavy metal-tolerant flora into smelting wastewater containing heavy metals can enhance the adsorption and transformation ability of communities to heavy metals. After colonization in the system, they form a symbiotic or cooperative relationship with the original microorganisms to jointly resist environmental stress and create a community structure that is more suitable for the harsh conditions found in specific wastewater.

4.3 Directional Enrichment and Application of High-Efficiency Functional Strains Aiming at Treatment Efficiency

For the directional enrichment and application of high-efficiency functional strains, the aim is to strengthen the degradation ability of communities to refractory pollutants and accelerate the removal speed of pollutants by increasing the proportion of key strains. Due to their stable chemical structure, refractory pollutants in industrial wastewater (such as dyes, polycyclic aromatic hydrocarbons, pesticide residues, etc.) are resistant to decomposition by ordinary microorganisms, often resulting in the treatment system's effluent not meeting the standard. However, highly efficient functional strains can rapidly degrade these substances through special metabolic ways (such as producing specific enzymes).

When directionally enriching such strains, we need to build a selective culture system with the target pollutants as the only carbon or energy source. For example, when treating wastewater containing azo dye, we use this dye as the only substrate of the culture medium, so that the strains that can degrade it can dominate the competition and multiply in large quantities. When treating wastewater containing petroleum hydrocarbons, petroleum hydrocarbons are used as the only carbon source to enrich hydrocarbon-degrading bacteria. During the enrichment process, the growth of the target strain can be further promoted by adjusting some conditions, such as the culture temperature and dissolved oxygen.

In practice, we introduce the enriched and efficient strains into the treatment system to establish a dominant population within the community. These strains not only directly degrade refractory pollutants, but also promote the synergistic effect of other microorganisms by secreting signal substances or metabolites. For example, the intermediate products produced by some high-efficiency bacteria after degrading pollutants can be used as nutrients for other flora to form degradation chains.

To sum up, through directional enrichment and application, the degradation efficiency of specific pollutants can be significantly enhanced. This results in a shorter treatment cycle and a reduction in the residual amount of pollutants, ultimately optimizing the overall treatment efficacy.

5. Application Prospect and Development of Optimization Strategies of Microbial Community Structure

5.1 Key Problems in Application

Although the application of microbial community structure optimization in industrial wastewater treatment has achieved certain results, it still faces many problems in practical promotion.

The first is the instability of the optimization effect. Small fluctuations in the natural environment or wastewater quality, such as sudden changes in temperature and sudden increases in the concentration of toxic substances, may lead to the imbalance of optimized community structure, the inhibition of dominant functional flora, and the proliferation of weak flora or miscellaneous bacteria, resulting in a rebound decline in treatment efficiency. Due to its instability, many enterprises adopt a wait-and-see approach towards the optimization strategy, fearing that their previous efforts will be wasted in long-term operations.

Secondly, the implementation of cost control measures is challenging. In the domain of bioaugmentation, the screening, domestication, and large-scale culture of high-efficiency strains necessitate specialized equipment and continuous investment. Moreover, in environmental regulation, precise control of parameters such as nutrient ratio and dissolved oxygen also requires additional energy consumption or drug cost. For small and medium-sized enterprises, the cost may exceed the traditional treatment method, which limits the popularization of optimization strategies.

Finally, it is difficult to completely avoid ecological risks. After introducing foreign functional flora or domesticated flora, they may compete with local microorganisms outside the treatment system for resources and destroy the natural ecological balance. In addition, the metabolites of some flora may create new environmental risks, and the current evaluation system for such long-term ecological impacts is not perfect, which increases managers' concerns about the application.

5.2 Future Development Direction

Given the current problems, the future development of microbial community structure optimization strategies will focus on technology integration and efficiency improvement, showing the following directions.

First, it is necessary to combine bioinformatics technology to achieve precise regulation. The analysis of species composition and functional gene distribution in the community by metagenome sequencing is helpful to quickly locate the key functional flora and its metabolic pathway. As a result, it is more targeted to guide the optimization strategy. For example, when the efficiency of degrading a certain pollutant is low, the strain associated with the missing functional gene can be directly identified to avoid ineffective regulation [7].

Secondly, it is suggested to develop an intelligent real-time control system. The sensor and algorithm should be combined to monitor flora activity and pollutant concentration in real-time, and automatically adjust the nutrient dosage and dissolved oxygen level to achieve on-demand optimization. For example, when the activity of flora decreases, the system automatically supplements micronutrients to avoid the lag of manual adjustment.

Thirdly, it is necessary to promote multi-strategy collaborative applications. The effect of single environmental regulation or biological reinforcement is limited, and more attention will be paid to the combination of the two in the future. For example, create suitable conditions for the target flora through environmental regulation, and inoculate efficient strains, so that they can quickly colonize and become dominant populations, and improve the overall optimization effect.

Fourth, it is essential to explore low-cost green technologies. Develop recyclable biological carriers, such as porous materials made of agricultural wastes, to reduce the cost of flora attachment and culture. Screening local high-efficiency flora and reducing the ecological risk of exotic flora make the optimization strategy easier to popularize in small and medium-sized enterprises.

These studies will promote the optimization of microbial community structure from empirical adjustment to precision, intelligence, and cost-effectiveness, thus unlocking its potential for industrial wastewater treatment.

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