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Technical mechanism and application prospect of nitrogen and phosphorus removal in constructed wetlands

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Abstract

With the rapid development of industry and agriculture, a large amount of nitrogen and phosphorus pollutants are discharged into water bodies, resulting in increasingly serious water eutrophication problems. As an eco-friendly and low-energy wastewater treatment technology, constructed wetlands have shown significant advantages in removing nitrogen and phosphorus. This paper systematically reviews the technical mechanisms, influencing factors and optimization strategies of nitrogen and phosphorus removal in constructed wetlands, analyzes the innovations and challenges of existing technologies, and looks forward to the future development direction. The results showed that the removal rates of total nitrogen and total phosphorus in constructed wetlands could reach up to 82.1% and 87.74%, respectively, through matrix optimization, microbial community regulation and process innovation. These findings provide an important reference for the further improvement and application of constructed wetland technology.

Keywords

Constructed wetland; nitrogen and phosphorus removal; removal mechanism; matrix optimization; Ecological treatment.

1. Introduction

Water eutrophication has become a global water environment problem, mainly due to the deterioration of water ecosystems caused by excessive nutrient inputs such as nitrogen and phosphorus [1]. These nutrients are mainly derived from agricultural drainage, domestic sewage and industrial wastewater. Although the traditional sewage treatment process can effectively remove organic matter, the removal effect of nitrogen and phosphorus is limited, and there are problems such as high operating costs and possible secondary pollution. Therefore, it is of great significance to find an efficient, economical and environmentally friendly nitrogen and phosphorus removal technology.

As an ecological sewage treatment technology, constructed wetlands can effectively remove nitrogen and phosphorus and other pollutants from sewage by using the physical, chemical and biological synergy of the matrix-microorganism-plant complex system. Compared with traditional treatment processes, constructed wetlands have the advantages of low construction and operation costs, simple maintenance and management, and significant ecological and environmental benefits, especially suitable for sewage treatment in small and medium-sized towns, rural areas, and remote areas [2].

Based on the latest research results of nitrogen and phosphorus removal in constructed wetlands, this paper systematically analyzes the removal mechanism of nitrogen and phosphorus in constructed wetlands, discusses the key influencing factors, summarizes the design optimization strategies, analyzes the treatment effect through application cases, and finally puts forward the prospect of future research directions, in order to provide theoretical

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reference for the optimization and popularization and application of constructed wetland technology.

2. Mechanism of nitrogen and phosphorus removal in constructed wetlands

The process of nitrogen and phosphorus removal in constructed wetlands is a complex integrated ecosystem project involving the synergy of multiple mechanisms. These mechanisms include processes such as physical filtration, chemical reactions, and biological metabolism, which work together to achieve efficient removal of pollutants.

2.1. Nitrogen removal pathways

The removal of nitrogen in constructed wetlands is mainly completed by microbial-mediated nitrification-denitrification. The nitrification process takes place in an aerobic environment, where ammonia-oxidizing bacteria and nitrite-oxidizing bacteria gradually convert ammonia nitrogen (NH_4^+-N) into nitrite nitrogen (NO_2^--N) and nitrate nitrogen (NO_3^--N) [3]. The denitrification process is carried out under hypoxic conditions, and denitrifying bacteria use organic carbon sources as electron donors to reduce nitrate nitrogen into nitrogen and release it into the atmosphere.

Studies have shown that there are other denitrification pathways such as simultaneous nitrification-denitrification (SND) and anaerobic ammonia oxidation in some constructed wetland systems. For example, researchers from Huazhong Agricultural University have established a system that combines simultaneous nitrification-endogenous denitrification and enhanced biological phosphorus removal in intermittent aeration constructed wetlands, and the total nitrogen removal rate can still reach 96.21% even under the condition of carbon source restriction.

Table 1: The main pathways and characteristics of nitrogen removal in constructed wetlands

Removal pathways	Reaction conditions	Major microorganisms	The final product	Influencing factors
nitrification	Aerobic	Ammonia-oxidizing bacteria, nitrite-oxidizing bacteria	nitrate	Dissolved oxygen, temperature, pH
Traditional denitrification	anoxia	Denitrifying bacteria	nitrogen	Carbon source, temperature, C/N ratio
At the same time, nitrification-denitrification	Aerobic/anoxic interface	Heterotrophic nitrifying bacteria, aerobic denitrifying bacteria	nitrogen	Microbial community structure
Anaerobic ammonia oxidation	Anaerobic	Anaerobic ammonia oxidizing bacteria	nitrogen	Substrate type,

Removal pathways	Reaction conditions	Major microorganisms	The final product	Influencing factors
				temperature

2.2. Removal route of phosphorus

The removal of phosphorus in constructed wetlands is mainly completed by adsorption and precipitation of the substrate. Metal ions such as calcium, iron, and aluminum in the matrix react with phosphate to form insoluble precipitates (such as $Ca_5(PO_4)_3OH$, $FePO_4$, $AlPO_4$), thereby fixing phosphorus. In addition, plant uptake and microbial assimilation are also important pathways of phosphorus removal, but this part is relatively small, usually accounting for only 5-15% of the total removal.

The research of Li Ruihua's team at Nanjing University found that when natural pyrite is used as a matrix, its iron-containing metabolites can form precipitation with phosphate ions, and pyrite can also be used as an electron donor for autotrophic denitrification, synergistically promoting the removal of nitrogen and phosphorus. After three years of operation, the removal rates of total phosphorus and total nitrogen in the pyrite-limestone mixed matrix wetland reached 87.7±14.2% and 69.4±21.4%, respectively.

2.3. Plant-microbe-substrate interactions

There is a close synergistic relationship between plants, microorganisms and substrate in constructed wetlands. Plant roots provide a surface for microorganisms to attach to and grow, and create a microenvironment by releasing oxygen and secretions; Microorganisms are responsible for degrading pollutants; The matrix provides the adsorption interface and reaction site. This synergy significantly enhances the system's decontamination capabilities.

The results show that plant roots can form an aerobic-hypoxic-anaerobic microenvironment sequence, which is equivalent to many A^2/O units connected in series or parallel, so as to simultaneously complete the nitrification, denitrification and phosphorus adsorption and precipitation processes. Additionally, organic matter secreted by plant roots provides an additional source of carbon for microorganisms, promoting the denitrification process.

3. Analysis of influencing factors

The efficiency of nitrogen and phosphorus removal in constructed wetlands is affected by a variety of factors, including hydraulic parameters, substrate type, plant selection, microbial community, and operation mode. Understanding these factors is of great significance for optimizing the design of constructed wetlands and improving treatment efficiency.

3.1. Hydraulic parameters and hydraulic loads

Hydraulic load and hydraulic residence time are key design parameters that directly affect the removal of contaminants. Studies have shown that the removal rate of nitrogen and phosphorus usually tends to decrease with increasing hydraulic load. When the hydraulic load increased from 0.03-0.1 m/d to 0.2-0.3 m/d, the total nitrogen removal rate decreased by about 15-20%.

Hydraulic residence time (HRT) determines the contact time between pollutants and substrates and microorganisms [4]. Proper HRT ensures that nitrification and denitrification processes are adequately carried out, while too short HRT can cause contaminants to flow out of the system without adequate treatment. Generally, the HRT of constructed wetlands is designed for 2-5 days, but the specific value needs to be determined according to the influent water quality and treatment goals.

Table 2: Removal effects of constructed wetlands on nitrogen and phosphorus under different hydraulic residence times

Hydraulic dwell time (days)	COD removal rate (%)	Ammonia nitrogen removal rate (%)	Total nitrogen removal rate (%)	Total phosphorus removal rate (%)
1	60-70	45-55	30-40	40-50
2	70-80	65-75	50-60	60-70
3	80-85	75-85	60-70	70-80
5	85-90	85-95	70-80	80-90

3.2. Substrate types and combinations

Substrate is the core component of constructed wetlands, which not only provides growth carriers for plants and microorganisms, but also directly participates in the removal process of pollutants, especially for phosphorus adsorption and precipitation. Common matrix materials include gravel, zeolite, limestone, biochar, etc., and the removal effect of different substrates on nitrogen and phosphorus is significantly different.

The "low-cost refractive efficient nitrogen and phosphorus removal wetland combination matrix system" developed by Tongyuan Environment adopts a hierarchical and layered combination of gravel, zeolite, limestone and sludge biochar to remove ammonia nitrogen through the adsorption and nitrification of zeolite in the aerobic zone, and provides carbon source for enhanced denitrification through limestone and sludge biochar in the anoxic and anaerobic zones, and enhances the removal of phosphorus by the adsorption, ion exchange and complexation of sludge biochar. This combined matrix system maximizes the nitrogen and phosphorus removal effect of constructed wetlands.

3.3. Temperature and seasonal changes

Temperature is an important environmental factor affecting the operation effect of constructed wetlands, which directly affects microbial activity and plant growth. Studies have shown that temperature has a particularly significant effect on nitrogen removal, with nitrogen removal rates typically 20-30% higher in summer than in winter. The operation data of Qixing Wetland showed that the removal rates of COD, ammonia nitrogen and total phosphorus during the plant growth period (May to October) were 35.3%, 37.9% and 52.9%, respectively.

In order to mitigate seasonal fluctuations, measures that can be taken include: increasing winter insulation measures (such as covering greenhouse film), selecting low-temperature resistant plant varieties, and adjusting winter operating parameters (such as extending hydraulic residence time). These measures help maintain the treatment effect of constructed wetlands under low temperature conditions.

4. Design optimization and innovation

To improve the efficiency of nitrogen and phosphorus removal in constructed wetlands, researchers have developed a variety of optimization technologies and innovative processes, including matrix improvement, structural innovation, and process enhancement. These innovations have significantly improved the performance and applicability of constructed wetlands.

4.1. Optimization of matrix combination and filling method

Substrate combination optimization is a cost-effective method to improve the efficiency of nitrogen and phosphorus removal in constructed wetlands. Reasonable combination according to the characteristics of different substrates can give full play to the advantages of various substrates and achieve synergy. For example, the removal rates of total phosphorus and total nitrogen remained at high levels of 87.7±14.2% and 69.4±21.4%, respectively, after 3 years of operation.

The layered fill strategy is also an important aspect of optimizing the design. According to the operation experience of pyrite constructed wetlands, pyrite can be arranged at the bottom and end of the constructed wetland, so that aerobic oxidized pyrite can be reduced while reducing the sulfate ion content in the effluent. This arrangement takes into account both the needs of chemical processes and microbial ecology.

Table 3: Effects of different combined matrix systems on nitrogen and phosphorus removal performance in constructed wetlands

Substrate combination	Configure the scale	Total nitrogen removal rate (%)	Total phosphorus removal rate (%)	Main mechanism of action
Pyrite + limestone	1:1 (Volume Ratio)	69.4±21.4	87.7±14.2	Autotrophic denitrification and chemical precipitation
Zeolite + limestone + biochar	Layered configuration	>80	>85	Adsorption, nitrification/denitrification, ion exchange
Gravel + zeolite + sludge biochar	Graded filling	82.1	87.74	Provide carbon source, adsorption, and microbial degradation
Bioceramite + pebbles	Upper/lower level	36.35-72.40	44.69-57.32	Microbial film formation, physical filtration

4.2. Optimization of hydraulic structure and flow state

Traditional constructed wetlands have problems such as short flow and dead zones, resulting in low effective utilization. In order to improve the water flow state, researchers have developed new hydraulic structures such as refractive flow and tidal flow. The baffle design extends the water flow path by setting up a baffle to increase the contact time between the pollutant and the substrate. Tidal flow changes the redox environment through periodic charging and drainage, promoting the alternation of nitrification and denitrification.

The refractored constructed wetland system developed by Tongyuan Environment creates an aerobic-anoxic-anaerobic area, and the water flow path is designed according to different functional zones, so that the sewage passes through different redox environments in turn, and the nitrogen and phosphorus removal process is optimized. This design minimizes short-flow phenomena and improves volume utilization.

4.3. Artificial reinforcement technology and intelligent regulation

For low-carbon nitrogen ratio sewage, constructed wetlands often have low nitrogen removal efficiency due to insufficient carbon sources. In response to this problem, electrolytic strengthening technology has been introduced into constructed wetland systems. The study by Zhong Le [5] et al. showed that the removal rates of NH_4^+-N, TN, and TP (88.30%, 82.10%, and 87.74%, respectively) from electrolytic tidal flow constructed wetlands were higher than those of unfortified wetland systems. The electrolysis process had a reducing effect on nitrate nitrogen, and the matrix near the anode contained more phosphorus-containing precipitates such as ferrite bonds, phosphorus oxide bonds, and hydroxypoly iron, which promoted the abundance of heterotrophic denitrifying bacteria and hydrogen-based autotrophic denitrifying bacteria, and achieved efficient and synchronous removal of nitrogen and phosphorus.

Intermittent aeration is another artificial enhancement technology that actively regulates the redox environment and promotes nitrification reactions by setting up aeration systems in constructed wetlands. Research from Huazhong Agricultural University shows that the establishment of enhanced biological phosphorus removal technology in intermittent aeration constructed wetlands, combined with simultaneous nitrification-endogenous denitrification reaction, can achieve a phosphate removal rate of 92.68% and a total nitrogen removal rate of 96.21% even with ordinary gravel as a matrix.

5. Challenges and prospects

Although constructed wetland technology has made significant progress in nitrogen and phosphorus removal, it still faces many challenges in practical application and needs to be further studied and solved.

5.1. Technical Challenges

First, the decrease in efficiency in low-temperature environments is the main technical challenge faced by constructed wetlands. Studies have shown that the nitrogen removal rate of constructed wetlands in winter tends to be 20-30% lower than in summer. This is mainly due to low temperatures inhibiting microbial activity and plant growth. While insulation measures can alleviate this problem to some extent, it will increase construction and operating costs.

Secondly, the problem of substrate saturation and renewal cannot be ignored. Especially for phosphorus removal, the removal rate will decrease significantly after matrix adsorption saturation. How to cost-effectively renew or regenerate saturated substrates is a practical problem that needs to be solved. At present, most of the research focuses on the development of new substrates, and the research on substrate regeneration technology is relatively insufficient.

Third, the collaborative treatment of complex pollutants is also a challenge. Actual sewage not only contains nitrogen and phosphorus, but may also contain heavy metals, persistent organic pollutants, pathogens, etc. These contaminants may affect microbial community structure, which in turn affects the efficiency of nitrogen and phosphorus removal.

5.2. Future development direction

The future development direction of constructed wetland technology mainly includes the following aspects:

The development of new matrix materials is the key to improving the efficiency of nitrogen and phosphorus removal. Future research should focus on low-cost, high-efficiency, and sustainable matrix materials, such as industrial by-products and modified natural materials. At the same time, attention should be paid to the long-term stability and regeneration ability of the substrate to extend its service life.

The refinement of ecological dynamics model is the theoretical basis of optimal design. Most of the existing models are based on empirical parameters and have limited universality. In the future, it is necessary to strengthen the mechanism research on the internal processes of constructed wetlands, establish more accurate ecological dynamics models, and improve the prediction ability and design accuracy.

Composite technology and process innovation are inevitable choices to solve complex pollution problems. In the future, the integration of electrolysis enhancement, aeration enhancement, membrane separation and other technologies with constructed wetlands should be strengthened to form a synergistic composite technology system to improve treatment efficiency and stability.

Smart operation and maintenance and management are important means to ensure the long-term stable operation of constructed wetlands. Combined with the Internet of Things, big data and artificial intelligence technology, build an intelligent monitoring and management system to realize real-time monitoring and intelligent regulation of the operation status of constructed wetlands, and improve operation efficiency and management level.

6. Conclusion

As a green and low-carbon sewage treatment technology, constructed wetlands have unique advantages and application prospects in removing nitrogen and phosphorus. Through systematic analysis, the following conclusions are drawn:

First, nitrogen and phosphorus removal in constructed wetlands is a complex process that involves various mechanisms such as microbial transformation, plant uptake, and substrate adsorption. Among them, microbial processes play a leading role in nitrogen removal, while matrix chemistry is essential for phosphorus removal. By optimizing the design, the synergy efficiency of various mechanisms can be improved.

Secondly, the treatment effect of constructed wetlands is affected by a variety of factors, including hydrological parameters, substrate type, temperature changes, and operation mode. In actual engineering, it is necessary to optimize the configuration of these parameters according to the specific water quality and water conditions and treatment goals to achieve the best treatment effect.

Third, through technological innovation and optimized design, the nitrogen and phosphorus removal efficiency of constructed wetlands can be significantly improved. Innovative technologies such as pyrite matrix, refractive flow structure, electrolytic strengthening and intermittent aeration provide effective solutions to solve the challenges of low-carbon nitrogen specific wastewater treatment and low temperature efficiency reduction.

Finally, there is still a lot of room for development in constructed wetland technology in terms of theoretical models, material development and system optimization. Future research should focus on mechanism exploration, material innovation and intelligent control to promote the high-quality development and widespread application of constructed wetland technology.

In summary, constructed wetland technology has broad application prospects, and through continuous innovation and optimization, it is expected to become an important technical choice for sewage nitrogen and phosphorus removal in the future, and make important contributions to the prevention and control of water environmental pollution and water ecological protection.

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