Mechanism and Application of Constructed Wetlands in Sewage Treatment

Yaxin Wu *

School of Resources and Environmental Engineering, Hefei University of Technology, Anhui, Xuancheng, China

* Corresponding Author Email: 2021218445@mail.hfut.edu.cn

Abstract. In recent years, with the increasingly serious problem of global water pollution, constructed wetlands with high efficiency, high adaptability and low cost, as an effective wastewater treatment technology has been widely studied and applied. This article mainly introduced the common types of constructed wetlands, including surface flow constructed wetlands, subsurface flow constructed wetlands and a variety of composite constructed wetlands, and the mechanism of microorganisms, plants and substrates in constructed wetlands. Differently constructed wetlands are suitable for different scenes. It can be seen from the data that the constructed wetlands with different compositions have good effects on the removal of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH_4^+-N) in sewage. Microorganisms have good removal and transformation effects on nitrogen and phosphorus, and the application of biofilm technology also has good prospects and value. Plants can be used in the absorption and transformation of heavy metals. The adsorption of the matrix is mainly a physical process, which uses its loose porous and large specific surface area to adsorb pollutants. Artificial wetlands have a positive impact on sewage treatment and are conducive to the construction of ecological civilization.

Keywords: Constructed wetland; microorganisms; plants, substrate; integrated constructed wetland.

1. Introduction

Artificial wetlands are a new type of sewage ecological treatment technology that began to develop in the 1970s [1]. An artificial wetland is a ground similar to a swamp that is constructed and controlled by humans. It mainly utilizes the synergistic effect of soil, artificial media, plants, and microorganisms to carry out physical, chemical, and biological processes on wastewater, thereby improving water quality. Due to the continued pollution of total nitrogen, total phosphorus, ammonia nitrogen, suspended solid particles, and heavy metals in the tailwater of sewage treatment plants, direct discharge of the tailwater into surface water can cause significant pollution, which may lead to eutrophication and waste of water resources. The use of artificial wetlands can achieve better sewage treatment levels at a lower cost and also has ecological and social benefits. The technology of artificial wetlands for wastewater treatment first appeared in Germany, and China introduced this technology in 1988 and began researching and applying it [1].

The ability of artificial wetlands to treat wastewater has been widely studied and applied in recent years. Its mechanism of action includes adsorption, filtration, oxidation-reduction, microbial decomposition, transformation, and other pollutants directly or indirectly in water bodies. Artificial wetlands have good removal effects on various pollutants, including organic matter, nitrogen, phosphorus, etc. Research shows that the removal rate of pollutants such as COD, BOD, TN, TP, etc. in constructed wetlands can reach over 70% [2]. This is mainly attributed to the joint action of plants, fillers, and microorganisms in wetlands. Generally speaking, the removal rate of heavy metals is 20% -70% [3]. After being treated with artificial wetlands, the treated sewage can be used for irrigation, groundwater replenishment, and industrial or urban water use, to achieve the reuse of water resources and alleviate water scarcity.

This article mainly introduces the composition, treatment processes, and treatment effects of different composite artificial wetlands, as well as their basic mechanisms of action.

2. Working Principle of Constructed Wetland

The treatment of wastewater by constructed wetlands mainly relies on three aspects of action: physical action, chemical action, and biological action. These functions collaborate in artificial wetlands to achieve the purification of wastewater. The basic components of artificial wetlands include microorganisms, plants, and substrates. Microorganisms in wetlands convert organic pollutants into harmless substances through biochemical reactions such as decomposition, transformation, and absorption. The roots of plants can absorb and adsorb pollutants such as heavy metal ions and nutrients in wastewater. The fillers and plant roots in artificial wetlands have physical functions such as interception, filtration, adsorption, and retention. These functions can effectively remove pollutants such as suspended solids, organic matter, and nutrients from wastewater.

2.1. Microbial Assimilation

In a constructed wetland ecosystem, microorganisms play an important role in symbiotic health and the migration and transformation of pollutants. The reproduction speed of microorganisms is very fast, and the population grows rapidly. They can quickly and effectively adapt to environmental changes and changes in pollutant concentration, and respond to pollution accidents promptly. Microorganisms are sensitive to environmental changes and can adjust metabolic activities and growth strategies according to environmental changes, which has good ecological safety. The purification effect under the action of microorganisms is stable, and the treated water quality is good, and suitable for various types of wastewater treatment.

The microbial community can be divided into aerobic, facultative anaerobic and anaerobic bacteria. The species diversity of aerobic bacteria is rich, which has a good effect on metal oxidation. To survive, some microorganisms will absorb or adsorb the required heavy metal ions from the outside to the cell [4]. Some bacteria release proteins during the growth process, which can convert soluble heavy metals in solution into precipitation Microorganisms can play a catalytic role in the treatment of heavy metal wastewater [4]. It was found that the activities of aerobic microorganisms in the plant root zone enhanced the adsorption and enrichment of heavy metals in the wetland. Anaerobic bacteria mostly play a role in the reduction reaction. The transformation and removal of nitrogen in constructed wetlands are mainly realized by ammoniation, nitrification and denitrification. Xu et al. reported some microorganisms in Actinobacteria, Firmicutes and Proteus have the function of converting organic nitrogen into ammonium, while Acinetobacter, Pseudomonas and spores have the function of denitrification while nitrifying bacteria and nitrifying spirochetes have the function of nitrification [2]. Proteus is mainly involved in the removal of phosphorus α Proteus β Proteus and γ Proteus is dominant [2].

In addition to playing a role in the natural state, microorganisms can also strengthen the role of microorganisms through artificial biofilm technology. Biofilm technology has the advantages of high efficiency, economy, and environmental protection. The utilization of microbial assimilation in artificial wetlands mainly relies on biofilm technology. The basic principle of biofilm treatment technology is to let the microbial filter media adhere to the medium, and when the sewage passes through the medium, it can be purified by microorganisms. In the study of Zhang et al, in the five experimental stages of urban sewage treatment by biofilm-enhanced constructed wetland, the first stage was a lack of treatment effect because the microorganisms in biofilm did not form a large regular community. In the second to fifth stages, the treatment effect of the BBRF packing unit is stable, and the organic matter removal rate is 70% to 80%. Biofilm not only has a strong removal ability for organic matter in wastewater but also can adapt to different water quality and environmental conditions. In addition, biofilm technology has a small footprint, simple operation, low operating costs, and can promote ecological balance and reduce environmental pollution [5].

2.2. Absorption of Plants

The existence of large aquatic plants is one of the most significant characteristics of constructed wetlands, which is also the reason why constructed wetlands are different from soil filters. Wetland plants can be divided into four types according to different life forms, including emergent, floating leaf rooted and submerged plants [6]. Plants in constructed wetlands can directly absorb and utilize nutrients such as nitrogen and phosphorus in sewage, to reduce the pollution of these substances in water bodies. The roots of plants can absorb heavy metals and other harmful substances in sewage and store or metabolize them. The roots of plants can also provide places for microorganisms to attach and grow, forming biofilms.

In constructed wetlands, Canna, iris, reed, Typha and Allium are the most widely used plants in the world [6]. Typha latifolia has excellent performance in absorbing nutrients. It can effectively absorb nutrients such as nitrogen and phosphorus, thus helping to reduce the burden of water eutrophication. In addition, it can also adsorb and enrich some toxic and harmful substances, such as heavy metals such as lead, cadmium, mercury, arsenic. Phragmites australis can absorb nitrogen, phosphorus, potassium and other substances in sewage, and can also adsorb and enrich heavy metals. In addition, Phragmites australis can also deliver oxygen to the water body, increase the activity of the water body, and play an important role in controlling water pollution and degrading harmful substances. Wu et al. found that wetland plants have good enrichment ability for Cd, Cr and Pb, in which Cd>Pd>Cr. Solanaceae has the strongest ability to accumulate Cd. Araceae and Araceae have the strongest Pb enrichment ability; Araceae and Cyperaceae have the strongest Cd accumulation ability. For Pb, leaf>stem>root. For Cr, root>stem>leaf. For Pb, root>leaf>stem [7].

2.3. Adsorption of Matrix

Matrix adsorption is an important way of removing antibiotics and heavy metals in constructed wetlands. Common substrates mainly include vermiculite, zeolite, river sand, peat, paddy soil, blast furnace slag, diatomite, volcanic rock, potassium feldspar and gravel [8]. Zeolite is a kind of aluminosilicate. As the substrate of constructed wetland, its role is mainly to remove pollutants such as ammonia nitrogen and phosphorus in sewage through adsorption and ion exchange. Zhang et al. showed that zeolite has the characteristics of a huge surface area and the nonclose combination of equilibrium cations in the framework and the framework, and has good adsorption capacity [5]. Because zeolite has strong selective adsorption for ammonium nitrogen, it can quickly intercept ammonia nitrogen in sewage, which can also achieve a good ammonia nitrogen removal effect. Therefore, in the whole experimental stage, the ammonia nitrogen removal effect of the system is very obvious, and the ammonia nitrogen removal rate can exceed 80%. Other adsorption matrices also have properties similar to zeolite. Volcanic rock, gravel, sand and gravel have the characteristics of rich reserves, low prices and direct mining in the local area. However, some natural minerals are easy to be blocked, plants cannot grow or the decontamination effect is poor.

Substrate plays an important role in the phosphorus removal process of constructed wetlands, and the adsorption and removal effect of substrate on phosphorus is greater than that of microorganisms and plants. In the study of Yang et al., among the factors affecting the phosphorus removal effect of the matrix, the adsorption capacity increased with the increase in temperature. In the isothermal experiment, under the condition of 30 ℃, the theoretical saturated adsorption capacity in the Langmuir equation is steel slag, ceramsite, volcanic rock, Maifan stone and gravel in descending order. When the pH range of sewage is 5.5 to 9.5, the optimal pH for phosphorus removal by ceramsite, volcanic rock and gravel is 5.5, and the optimal pH for steel slag is 9.5 [9].

3. Type of Constructed Wetland

3.1. Basic Constructed Wetland

Constructed wetlands can be divided into free surface flow constructed wetlands (SFW) and subsurface flow constructed wetlands (SSFW) according to their different hydraulic forms and treatment methods. The surface flow constructed wetland is similar to the natural wetland. The water body is located above the substrate layer of the wetland, and its water depth is generally 0.3-0.5 meters. Sewage flows through the surface of the wetland and is purified by evaporation, infiltration and overflow. This type of constructed wetland has the advantages of less investment, simple operation and low operation cost. The subsurface flow constructed wetland mainly flows under the surface of the wetland bed, and is purified by the biofilm growing on the surface of the filler, plant roots, and the interception of topsoil and filler. According to the different flow directions of sewage in the wetland, the subsurface flow wetland system can be divided into horizontal subsurface flow constructed wetland and vertical subsurface flow constructed wetland. This type of wetland has the advantages of high removal efficiency and large hydraulic load. Vertical flow constructed wetland is another form of subsurface flow wetland. In the process of sewage flowing horizontally from one end of the water inlet, it flows to the other end of the water outlet through sand, medium and plant roots to achieve the purpose of purification.

In the process of actual application of the above constructed wetlands, generally, one kind of constructed wetlands will not be used alone, but a variety of constructed wetlands and oxidation ponds and other facilities are used together to achieve better treatment effects. The subsurface flow constructed wetland has a large hydraulic load and better pollutant removal efficiency, but the cost of infrastructure construction is high, the management and maintenance are cumbersome, and it is prone to blockage. The surface flow constructed wetland has the advantages of simple structure, relatively low construction cost and relatively easy management and maintenance, but it occupies a large area and has a small hydraulic load. To make the treatment effect of constructed wetlands better, and with the development of science and technology, people use more composite constructed wetlands. This paper introduces the combined surface flow constructed wetland, subsurface surface flow composite constructed wetland, horizontal subsurface flow constructed wetland, combined vertical flow constructed wetland, cascade ecological wetland, free surface constructed wetland, composite subsurface flow tidal flow constructed wetland.

3.2. Combined Surface Flow Constructed Wetland

The combined surface flow constructed wetland is a series of multiple surface flow constructed wetlands to enhance the effect of sewage treatment with a large area. A three-stage surface flow wetland constructed by Xu et al. was used to treat low-concentration piggery wastewater. The average mass concentrations of $COD, TN, NH_4^+ - N, TP$ in the low-concentration piggery wastewater before treatment were 87.7, 32.3, 39.3 and 3.3 mg/L , and the average mass concentrations after three-level constructed wetland treatment were 20.0, 8.7, 11.4 and 0.5 mg/L. The constructed wetland can remove 77% (COD), 73% ($TN,$), 71% ($NH_4^+ - N$) and 84% (TP) of various pollutants in the wastewater. The effect of this combined wetland is better than that of general sewage treatment plants [2].

3.3. Subsurface Surface Flow Composite Constructed Wetland

The subsurface surface flow composite constructed wetland makes full use of the characteristics of the subsurface flow constructed wetland and surface flow constructed wetland and effectively combines the advantages of the two wetlands, which can improve the effect of river sewage treatment, create richer habitats and improve the stability of the constructed wetland ecosystem. Liu et al. designed and manufactured a stepped composite constructed wetland system with subsurface flow at the front end and surface flow at the back end, aiming at the serious water environment pollution of small rivers in the Taihu Lake Basin. Sidegrass with a density of 25 plants/m^2 was planted in the experimental area. The results showed that when HTR was 3.4 days, the average removal rates of $TN, TP,\ NH_4^+ - N$ and HMI reached 64.3% from July to December, respectively 9%, 74. 6%, 51. 1%. Compared with the separate subsurface flow constructed wetland under the same conditions, the removal efficiency of pollutants increased by 12.1%, 10.6%, 1.8% and 5.1% respectively [10].

3.4. Horizontal Subsurface Flow Constructed Wetland

The main advantages of horizontal subsurface flow constructed wetlands are as follows. It makes full use of the space of constructed wetland and gives full play to the synergy between systems (plants, microorganisms and substrates), so its treatment capacity is significantly improved compared with that of surface flow constructed wetland system under the same area. The sewage flows below the ground with a good thermal insulation effect, which is suitable for sewage treatment in cold areas. The sanitary conditions are good and there is no odor, so it is widely used. Yao et al. chose to study the constructed wetland unit in the water quality improvement project of the mainstream system in the upper reaches of the Fenhe River. The project adopted the model of sediment deposition and enhanced mobile biofilm reactor biological system+multi-layer medium horizontal subsurface flow constructed wetland and surface oxidation pond, and achieved water purification through the synergistic effect of wetland plants (Lythrum Chelidonium, iris flavescens, Canna, etc.) and substrate biofilm microorganisms. The results show that this wetland structure has a good retention effect on microplastics greater than or equal to 800 μ m, which is mainly due to the retention effect of iris aurea which can remove some microplastics in natural water and the network structure formed by plant roots [11].

3.5. Combined Vertical Flow Constructed Wetland

From the perspective of practical application, the cost of combined vertical flow constructed wetland in construction is relatively low, but it has a good effect in removing ammonia, nitrogen, phosphorus and other nutrients. In combined vertical flow-constructed wetland in Wang's research, three vertical flow-constructed wetlands were connected in series, each with the same specification, and different fillers were used. The primary filler was zeolite, the secondary filler was quartz sand, and the tertiary filler was ceramsite. The wetland plants were Canna, Lythrum, iris, etc., and the density was 20 plants/m^2. The results showed that the combined vertical flow constructed wetland could effectively remove the total nitrogen in the sewage, and the first stage showed a higher removal effect. The proportion of ammonia nitrogen in the influent decreased from 83.5% to 32% in the effluent, but the proportion of nitrosamine increased from 1.5% in the influent to 67.4% in the effluent. This is mainly caused by volatilization, ammonification, nitrification, plant absorption and anammox to change the form of nitrogen in sewage. However, this method is relatively complex in operation and is greatly affected by climate factors and the natural environment, which to a large extent hinders the possibility of large-scale popularization and application of this technology in rural areas in China [13].

3.6. Cascade Ecological Wetland

Cascade ecological wetland integrates the advantages of ecological pond, surface flow wetland and subsurface flow wetland, and forms free water surface through the reasonable combination of each unit. Sewage flows through the ecological wetland by gravity to remove pollutants in the water. For example, the Wuxi tailrace cascade ecological wetland studied by Yao has a significant removal effect on various pollutants, and the pollutant concentration decreases along the way. The total average values of $COD, BOD,\ NH_4^+ - N,\ NO_3^- - N$ and PO_4^{3-} in the influent of the wetland are 20.84mg/L, 3.13 mg/L, 0.91 mg/L, 9.54 mg/L and 0.24 mg/L, respectively. The total average values of pollutants in the effluent are 16.27 mg/L, 2.34 mg/L, 0.52 mg/L, 6.85 mg/L and 0.11 mg/L, respectively, and the removal rates are 21.95%, 25.14%, 43.02% The pollutant reduction loads were 1.24, 0.21, 0.11, 0.73 and 0.03g (M/d), respectively [11].

3.7. Composite Subsurface Tidal Flow Constructed Wetland

Tidal flow constructed wetland is a water inlet and outlet mode of "instantaneous inlet and instantaneous outlet". It absorbs a large amount of air through the suction generated by the bed-wetting surface in the drainage gap, increases the oxygen content in the wetland, and strengthens the function of nitrogen and phosphorus removal. In the two-stage composite subsurface flow tidal flow constructed wetland constructed (IVCW-TFCW) by Zhang, et al., IVCW-TFCW can effectively purify slightly polluted river water when the average concentrations of $COD, NH_4^+ - N, TN, TP$ in the influent are 106.69, 9.36, 14.36 and 1.03 mg/L, respectively. The average removal rates of $COD, NH_4^+ - N, TN, TP$ are 93.79%, 98.62%, 77.24% and 18.16%, respectively. Among them, the removal rates of COD and $NH_4^+ - N$ by IVCW reached 87.38% and 97.29%. Based on this, the secondary tfcw1 was further purified to reduce the effluent concentration to 6.60 mg/L. and 0.13 mg/L [14].

4. Summary

Constructed wetlands can purify wastewater, reduce water pollution and protect biodiversity, which is of great significance for maintaining ecological balance and the natural environment. In this article, different types and mechanisms of constructed wetlands were introduced. The constructed wetland can treat wastewater through the joint action of microorganisms, plants and substrates, in which the removal rate of organic matter can reach 70% to 80%, even over 80% under good processing conditions, and the removal rate of heavy metals can reach 20% to 70%.

Through the combination of surface flow constructed wetland and subsurface flow constructed wetland, the composite constructed wetland is obtained, which makes the treatment effect of the constructed wetland better and the economic feasibility higher.

Different types of constructed wetlands are suitable for different scenarios. The composite constructed wetlands introduced in this paper include combined surface flow constructed wetlands, subsurface surface flow composite constructed wetlands, horizontal subsurface flow constructed wetlands, cascade ecological wetlands, and composite subsurface tidal flow constructed wetlands. By combining a single constructed wetland, the pollutants in sewage can be removed efficiently. The combined constructed wetland can make better use of local conditions, such as using gravity as the power of water flow, saving energy, and combining the advantages of surface flow constructed wetland and subsurface flow constructed wetland, so that the operation effect of the composite constructed wetland is better and the cost is reduced.

The development of constructed wetlands will be closely linked with sustainable development. With the progress and innovation of technology, the construction cost of constructed wetlands will gradually reduce, so that more people can enjoy the benefits of this environmental protection technology. In addition, future constructed wetlands will also focus on the protection and restoration of ecological diversity. In constructed wetlands, by planting a variety of plants and creating a diversified ecological environment, more microorganisms and animals can be attracted to inhabit and reproduce, thus forming a perfect ecosystem. This can not only improve the ecological environment quality of constructed wetlands but also realize the diversification of ecological functions and provide more ecological services for human beings.

References

[1] Zhou Kecheng, Liang Min, Rao Lijun. Sewage treatment technology of constructed wetland and its development and application. Leather Making and Environmental Protection Technology, 2022,3 (15): 32-34.

[2] Xu Shaoqi, Jia Kaixue, Xie Linqi, et al. Study on the deep purification effect of three-stage surface flow constructed wetland on pig farm Wastewater. Industrial Water Treatment, 2023,43 (07): 86-93.

[3] Luo Qian, Lin Fenglian, Yuan Feng, et al. Purification mechaism of four kinds of sewage heavy metal elements by plant rhizosphere microorganisms in constructed wetland. Southwest China Journal of Agricultural, 2022, 35(1): 176-185.

[4] Zhou Hailan. The application of constructed wetland for heavy metal wastewater treatment. Environmental Science and Management, 2007,32 (9): 89-91114.

[5] Zhang Lei, Zhang Juan. Mechanism analysis of biofilm enhanced constructed wetland for urban sewage treatment. Shanxi Chemical Industry, 2023,43 (6): 227-229.

[6] Jan vymazal, Wei Ting, Zhao Yaqian, et al. Counting the role of plants in constructed wetland for wastewater treatment. China Water & Wastewater, 2021,37 (2): 25-30.

[7] Wu Kun, Kong Xiao, Dong Yu, et al. Meta-analysis of the accumulation ablility of wetland plants to chromium, cadmium and lead in wastewater. Jiangsu Journal of Agriculture Sciences, 2022,38 (6): 1532-1540.

[8] Li Guowan, Huang Zhujian, Li Huashou, et al. Adsorption performance of different substrates to combined sulfamethoxazole and hexavalent chromium pollution in a constructed wetland. Journal of Agro-Environmental Sciences, 2023,42 (6): 1355-1367.

[9] Yang Zi, Wang Jiaquan. Study of adsorption properties of phosphorous by five constructed wetland matrixes. Journal of Hefei University of Technology: Natural Science Edition, 2012,35 (7): 981-986.

[10] Liu Chang'e, Song Xiangfu, Liu Fuxing, et al. Purification effect of integrated subsurface-surface flow constructed wetland. Environmental Pollution and Prevention, 2014,36 (8): 11-18.

[11] Yao Liang, Zhang Feng, Ben Rui, et al. Removal of microplastics in multilayer media horizontal subsurface flow constructed wetland. Environmental Pollution And Prevention, 2023,45 (2): 199-205.

[12] Wang Yun. Combined Vertical flow constructed wetland process and its sewage treatment effect. China Resources Comprehensive Utilization, 2018,36 (8): 66-68.

[13] Yao Hanshen Study on water quality improvement and process optimization of sewage plant tail water by cascade ecological wetland. Southeast University, 2022.

[14] Zhang Ziyu, Tian Weijun, Gao Huizi, et al. Study on the purification performance of integrated vertical subsurface flow and tidal flow combined constructed wetland substrate for slightly-polluted water body. Periodical of Ocean University of China, 2023, 53(8):104-112.

[15] Jin Boyan, Liu Yueting, Wang Zilong, et al. Influences on water properties of intermittent operation of constructed surface flow wetlands. Wetland Science and Management, 2022,18 (5): 19-23.

[16] Liang Qibin, Hou Lei, Li Nengfa, Chen Xin, Wang Keqin. Long term effectiveness and impact factors of nitrogen interception in surface flow constructed wetlands in northern Erhai Lake. Journal of Agricultural Environmental Sciences, 2020,39 (7): 1585-1593.

[17] Yan Hong, Zhang Chaofan, Ma Qiongfang, et al. Research on substrate screening and purification effect of constructed wetlands. environmental ecology, 2022,4 (9): 115-120.

[18] Yan Yuan, Ma Jiao, Dang Hongzhong, et al. Orthogonal experience to optimize vertical subsurface flow constructed wetland for short-cut nitrification. China Environmental Science, 2023,43 (3): 1177-1185.

[19] Li Meng, Zheng Huaqing, Liu Jiaheng, et al. Discussion on the efficiency and sustainability of the reclaimed water purification by constructed wetlands. Guangdong Chemical Industry, 2023,50 (11): 151-152167.