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A novel subsurface flow constructed wetland system used in anvanced wastewater treatment for nutrient removal in a cold area

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Due to the limitations of a cold climate to a conventionally constructed wetland system(CWS) during anual operation, a new type of compound double-layer subsurface flow wetland system was developed. A full-scale test trial of this system has been operated in the Northeast of China, which was used for advanced sewage treatment. By increasing the depth of the wetland structure, setting down insulating material layers, filling with a high-efficiency compound substrate and using the bioaugmentation technology. The purification efficiency and the operational stability of this CWS has been effectively improved. The new type of double-layer subsurface flow of the CWS still showed a high purification capacity for organic matter in the winter. It was hard to obtain a high purification effect for the ammonia with the wetland system in winter because of the limitation of nitrification at low temperatures, but the system had a significant effect in denitrification and nitrate-nitrogen removal. The compound substrates provide a high performance of the system in Total Phosphorus (TP) removal.

Key words: Constructed wetland; Horizontal subsurface flow; Nutrient Removal; Cold areas

INTRODUCTION

Contaminant and nutrient discharged from sewage into an aquatic environment can cause serious pollution and the nitrification of lakes, rivers and sea coasts and is one of the major environmental concerns in the world [16]. The traditional municipal wastewater treatment technology is a challenge to small towns, for it requires sophisticated maintenance and management, high investment and high running costs. Furthermore, the wastewater treatment systems used in small towns also cannot produce effluent with a high quality, especially in nitrogen and phosphorus removal. Therefore, it is of great importance to develop the process for advanced wastewater treatment in rural areas and small towns. The constructed wetland system (CWS) is an efficient system for secondary or tertiary sewage treatment and as such could significantly improve the quality of wastewater effluent [1,5,6]. CWSs are widely used for domestic wastewater, agricultural wastewater and industrial wastewater as these are cost-effective, technically feasible and enhance the landscape quality [11, 19].

In China, the constructed wetland system is very suitable for decentralized wastewater treatment in small towns and the countryside. However, the cold climate in the Northeast of China has negative effects on the conventional CWS while in operation through out the whole year [2, 17], which makes the CWS unsuitable in the traditional view for sewage treatment in the Northeast of China. This limits the field application of the constructed wetland system in north China. Nivala et al. [15] pointed out that the low temperatures could cause; the wetland system pipes to rupture, plant dormancy, rhizosphere microbial metabolism slow down or even system stoppage and other phenomena. The results indicated that the rate of nitrification and denitrification with temperature are positively correlated in constructed wetlands. The nitrogen removal is significantly impacted by the low temperature in winter, which is caused by the low activity of microbes and plants in the wetlands at low temperatures [7, 10]. In the cold winter, the low temperature of the water affects the operating efficiency of constructed wetlands, which can decrease the adsorption capacity of the media, increase the viscosity of the water, lower the diffusion rate, decrease the rate of water molecule transport in the roots, reduce the oxygen transfer efficiency, decrease the metabolic rate of the bacteria and plants, stimulate the accumulation of organic matter particles in the packed media and cause soil clogging. In addition, the temperature can affect the dissolved oxygen concentration and it will directly impact the aerobic treatment process. At low temperatures, the purification of the sewage by the wetland is not stable, which may lead to a suspension of function [12, 14]. In conclusion, the effective operation of traditionally constructed

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wetlands in the cold is elusive.

In cold regions, the design and construction of CWSs have special requirements on the structure of the wetland, the selection of media, and the insulation measures. Compared with natural wetlands, the pollutants removal rate of the constructed wetlands depends largely on the substrates. The contaminant removal in the wetland bed depends mainly on the purification of substrates and microorganisms, especially after the plants are harvested in the autumn and winter [11]. The cold climate can strongly affect the efficiency of CWSs as well as the wastewater characteristics and the filling material composing the wetland. Therefore, it is necessary to develop systems for low temperatures together with appropriate design and operational criteria. For the problems faced by CWSs in the cold winter, the Subsurface Flow Constructed Wetland is generally designed as a major wetland in the cold regions. The cover of the substrates on the surface of the subsurface flow constructed wetland can reduce the energy loss due to sewage evaporation, transportation and flow. It is able to maintain and improve the temperature inside the wetland, which can protect the constructed wetland internal micro-organisms from the influence of the external low temperature [22]. At present, several measures have been used to ensure the effective operation of the constructed wetlands and to improve the purification at low-temperature. It includes increasing the depth of the wetland structure, applying insulating materials, artificial aeration, extending the hydraulic retention time and effluent return. It is of great importance to solve the problem that CWSs cannot operate normally in the freezing winter and develop a highly efficient constructed wetland system to be used in cold areas, especially in small towns and the countryside to control the decentralized point source and non-point source pollution.

MATERIALS AND METHODS

Experiment site and raw water quality

A full-scale test trial of the system for advanced sewage treatment has been constructed and operated in the Harbin Taiping Wastewater Treatment Plant (45°49' 0.51"N, 126° 43' 8.91"E) in the northeast of China. The experimental site is in a sub-frigid monsoon climate zone which has a winter as long as 6 months and the lowest temperature in winter can be lower than -30°C. The average temperatures through out the trail period were -10°C in the winter (from February to April, 2010) and 23°C in the summer (from May to August, 2010).

The main purpose for developing the novel Subsurface Flow CWSs was to treat the secondary effluent of the small treatment plants, especially focused on total nitrogen (TN) removal, because most small sewage treatment plants in China are without the process for TN removal. The untreated water was the effluent of a high load sewage biological treatment reactor with a jet loop technology, which was focused on the COD (Chemical Oxygen Demand) and Ammonia Nitrogen removal with the aeration condition. The contaminant concentration range of the untreated water involved COD of 85~120 mg/L, SS (Suspended Solids) of 18~27 mg/L, NH_4^+-N (Ammonia Nitrogen) of 18~30 mg/L, TN (Total Nitrogen) of 24~45 mg/L, TP (Total Phosphorus) of 1.3~3.9 mg/L.

The configuration of the constructed wetland system

In accordance with the characteristics of the cold climate and the sewage composition in the northeast of China, a new type of the compound double-layer subsurface flow constructed wetland system has been developed based on the conventional CWSs research. As shown in Fig. 1, the system has a structure with two layers of horizontal subsurface flow wetland. The tank of the full-scale trial wetland system was constructed by a 5 mm welding steel plate with waterproof an epoxy coating and the total size of the tank was 11 m long × 4m wide × 3m deep. The system consists of three main parts, including: an influent tank (2m long), the double subsurface flow constructed wetland (8m long) and an effluent tank (1m long).

The core of the system consists of the two layers of horizontal subsurface flow wetland and the total size of the wetland tank was 8m long × 4m wide × 3m deep with each part having a 1.2m deep substrate layer and a baffle plate between the two layers. To improve the microorganism activity and remove the phosphorus, a compounded substrate was filled in the top layer with grit, haydite, cinders and lime stones, while the under layer was filled with gravel, volcanic rocks and lime stones.

Cold-proof measures and operation of the system

The two layer wetland of the system was operated in an alternating mode. In the winter the sublayer was operated as a bio-filtration bed and the top layer was frozen as a thermal insulation materials layer to protect the under layer from the cold weather. Another measure for cold-proof was to set a 10 cm cover of dry straw and reed over the top surface of the top layer wetland. The system can operate stably by the combined of cold-proof measures during the frozen winter. In the summer, the top layer was used and the contaminant was removed by the combined purification of the substrate, microorganisms and plants.

The untreated water from the biological reactor was introduced into the effluent tank and then the wastewater was fed to the wetland with a submerged pump (QDX1.5-16-0.37KW, Shanghai People Pump Factory Co., Ltd.). A pre-aeration device was equipped in the influent tank to improve the DO (Dissolved Oxygen) of wastewater. The effluent of the wetland system was discharged into the effluent tank and pumped out batch-wise with a submerged pump. There was another submerged pump placed in the effluent tank, which recirculates the water from the effluent tank to the front of the wetland in order to obtain a higher performance of organic matter and nutrients purification. The flow rate of the CWSs was 1.5-2m3/h monitored by an Electromagnetic Flow Meter (SITRANS F M MAGFLO MAG 1100, SIEMES Co., Ltd.) and the hydraulic retention time (HRT) was 19~26h. The top layer wetland was planted with reeds at a density of 16 rhizome/m2.

Rapid start-up with bio-augmentation

In order to render the system a rapid start-up and enhance the performance of organic and nitrogen removal in the frozen winter, the engineering bacterium agent with a psychrotolerant denitrification consortium obtained by fast enrichment and domestication [8] was added into the constructed wetland, which can remove the ammonia, nitrate and organic matter simultaneously and efficiently at a low water temperature (<10°C). At system start-up, 200L of bacterium agents were added to the wetland system every three days, 3 times in total.

Analytical methods of the effluent

The influent and effluent of the CWS was measured each day by detecting the chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), total nitrogen (TN) and total phosphorus (TP) according to the standard methods [2]. Every sample had been detected 3 times and the results shown in the paper were the average of the 3 time detections.

RESULTS AND DISCUSSION

The performance of the cold-proof measures

In order to investigate the performance of cold-proof measures, the temperatures of the influent, effluent and atmosphere in the system during the winter have been recorded (Fig.2). The temperature data shows that the atmospheric temperatures were low in the first month when the system was started, the average temperature was below -10°C and the lowest temperature reached about -25°C. The temperature of the influent was relatively stable, the average temperature was 13°C during the operational period in the winter and the lowest temperature was 11°C. The temperatures of the effluent show that the cold-proof measures designed in the system can significantly reduce the heat loss from the inner wetland and the average temperature of the effluent was 10.6°C during the winter operation period with an average temperature drop less than 3°C. The temperatures of wetland effluent could still be above 7°C in the coldest period (temperatures about -25°C), which can allow for normal system operation and stable purification. In contrast, a pilot-scale wetland system (volume 4 m^3) used in the previous winter was completely frozen when the air temperatures fell below -10°C. The results prove that the structural design of the double-layer constructed wetland and the cold-proof measures can make the system operate stably without freezing in the cold of Northeast China.

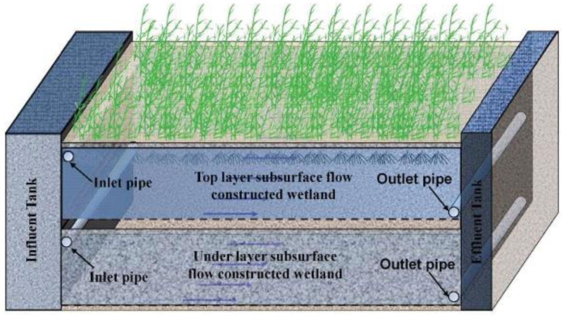

Fig.1 Double-layer subsurface flow constructed wetland system

Organic matters and suspended solids removal

The purification effect of the system on organic matter during the two periods (winter and summer) is shown in Fig. 3. The results indicate that the system had a good performance for organic pollutant removal under at a low temperature and high hydraulic loading operational conditions. The main purpose for developing the novel CWSs was for the advanced treatment of the secondary effluent of the small treatment plants, focused on Total-Nitrogen removal, but the system can also purify the organic contaminant. The effluent COD concentrations were 43 to 55mg/L in winter and 40 to 50mg/L in summer, while the influent COD concentration was 85 to 120 mg/L. The average effluent COD concentration of the CWSs was 46.4±4.3mg/L in winter and 41.4 ± 2.2mg/L in summer, the average removal rate of the COD was 51.5 % in winter and 57.0 % in summer. The bio-augmentation with adding the psychrotolerant bacterium consortium agent has obviously improved the organic removal performance at low temperature. The average removal rate of the COD was 44.2 % in the first ten days and then the removal rate has been improved to about 55 % after adding bacterium agent.

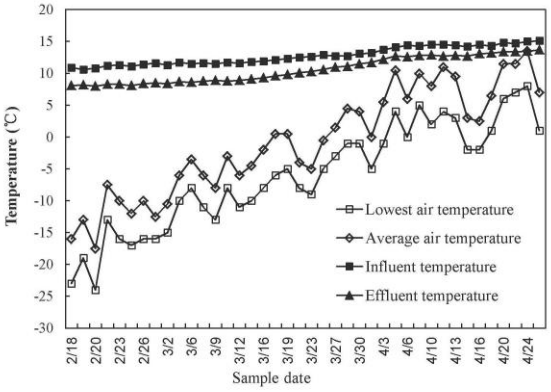

Fig. 2. The temperatures of the influent, effluent, and atmosphere in the system during the winter.

Furthermore, the CWSs had a good performance in Suspended Solid removal during the whole period of operation. The values for SS in the effluent were always lower than 10 mg/L and the effluent showed an excellent sensory indicator. The mechanisms of purification of SS by the wetland system mainly include the filtration of the suspended particulates with the substrate, the flocculation and settling of colloidal particulates with a bio-film attached to the substrate [4, 20]. This subsurface flow constructed wetland has played a role as a filter bed and the suspended solids have been removed effectively by the filtration of the fine and polyporous substrates.

The removal of the organic matter in the wetlands is largely regulated by microorganisms and their metabolism. The microbial biomass is a major sink for organic carbon and many nutrients. In the winter, the system was operated to purify the wastewater in the under layer. With the function of the top layer as an insulating materials layer and other anti-freezing measures, the inner temperature of the wetland has been improved significantly with the effluent at 8~10℃ in the frozen winter. Without plants, the under layer subsurface wetland acts as a fixed-film bioreactor and the bio-augmentation has been used to improve the purification ability at low temperatures. The contaminant was removed by the combined purification of the substrate and microorganisms. The mechanisms of the particulate organic matter removal were similar to suspended solids separation in the horizontal substrate beds. The dissolved organic matters from the influent or cycled from solids decomposition could likely be adsorbed on the biofilm surfaces attached to the media and they would be purified by the assimilation or degradation of the microorganisms. The predominant metabolic pathways leading to organic matter removal from the system were the aerobic reaction and denitrification. The aerobic reaction was most likely to occur in the front of the wetland because of the pre-aeration in the influent tank. The operation results suggest that the purification efficiency and the operation stability of the CWSs has been improved effectively by placing an insulating top substrate layer and surface materials cover filling into a high-efficiency compound substrate and applying the bio-augmentation technology. The new type of double-layer subsurface flow CWS still showed a high purification capacity of the organic matter in the winter.

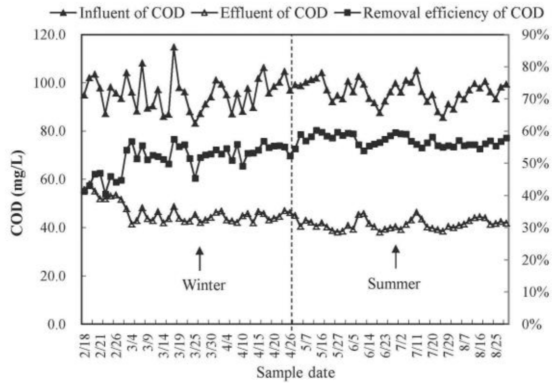

Fig. 3 The performance of COD removal in a CWS over the winter and summer.

Nitrogen removal

The concentrations of the TN, NH_4^+-N and NO_3^--N in the influent and effluent of the CWSs during the winter and summer periods has been measured and the statistical results of 40 samples in winter and 41samples in the summer is been shown in Fig. 4. The TN, NH_4^+-N, and NO_3^--N averager concentrations of effluent were 19.7 ± 4.5 mg/L (range from 14 to 29mg/L), 15.7 ± 3.9 mg/L (11 to 21 mg/L), 4.6 ± 2.5 mg/L (3 to 8 mg/L) in the winter, and 16.6 ± 3.6 mg/L (9 to 27mg/L), 7.6 ± 2.7 mg/L (5 to 16 mg/L), 6.3 ± 1.9 mg/L (4 to 11 mg/L) in the summer, while the TN, NH_4^+-N and NO_3^--N average concentration of influent were 34.0 ± 7.7 mg/L (24 to 45mg/L), 23.1 ± 5.1 mg/L (18 to 30mg/L) and 9.4 ± 3.6 mg/L (6 to 15 mg/L). This indicated that the under layer constructed wetland in the winter obtained a relatively higher removal rate of NO3$^-$-N (average 51%), but a lower rate of NH_4^+-N removal (average 32%) and the average removal rate of TN was 42% in the winter. In summer, the top layer constructed wetland, yields a much better performace for NH_4^+-N removal (average 67%) than that in the winter and the average removal rate of TN was 51%.

The predominant pathways for nitrogen (N) removal in CWSs contain the assimilation and storage by plants and microorganisms, burial of organic N and the production/release of N_2 [21]. In these processes, N_2 release represents the only permanent removal mechanism of N from the waste stream. The production of N_2 in wetlands has been principally attributed to the process of nitrification-denitrification and the anammox process can also contribute to the N_2 production in CWSs [9, 18]. For this constructed wetland, the nitrogen removal pathways from the top layer of wetland in the summer was the combined nitrification/ denitrification process by the microbes, the absorption and assimilation process by the plants. The under layer wetland can depend mainly on the nitrification/denitrification process to remove the nitrogen. On the other hand, the temperature was an important factor in the nitrification of constructed wetlands [23], the reaction likely slowed down by the low temperature. Therefore, by using this wetland system it was hard to obtain a high purification effect on the ammonia in the winter, but the system performed well in denitrification or the nitrate nitrogen removal at low temperatures.

Phosphorus removal

The purification performance of TP in the CWSs is shown in Fig. 5. The TP average concentrations of effluent were 0.49 ± 0.14 mg/L (0.38 to 0.69 mg/L) in the winter and 0.46 ± 0.13 mg/L (0.36 to 0.62mg/L) in the summer, while the influent TP average concentration was 2.10 ± 0.95 mg/L (1.3 to 3.9 mg/L). The results pointed out that the wetland system showed a good performance of phosphorus removal both in the winter and summer. The average removal rates of TP were 76.7% in the winter and 78.1% in the summer.

The mechanisms of phosphate removal from wetland systems mainly include the uptake by plants, the transformation by microorganisms and the precipitation/exchange/sorption by the substrates [13].

Since there is no important gaseous component in the biogeochemical cycle, phosphorus tends to move to the sediment sink in natural systems and become scarce in the ecosystem. In fact, it is the accretion of mineral phosphates and biomass in the sediment that is the primary mechanism for phosphorus removal in the wetland environment. The TP removal by the under layer wetland in the winter depends mainly on the adsorption of the substrates, the biofilm and the high performance of TP removal indicated, that the compound substrates of gravel, volcanic rocks and lime stones had a strong capability of phosphate removal.

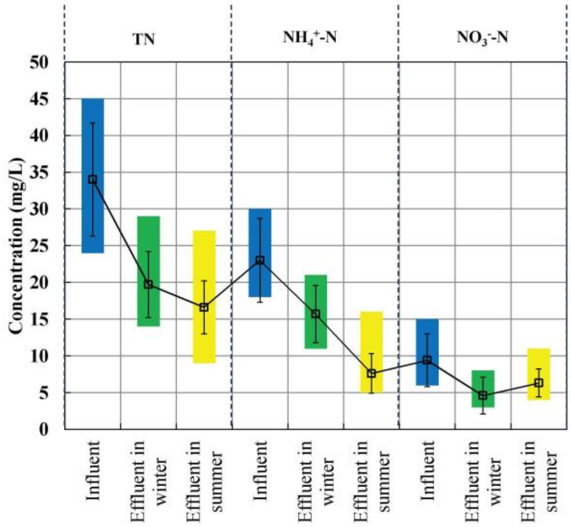

Fig. 4 Concentrations over the winter and summer of the Total Nitrogen, Ammonia Nitrogen and Nitrate-Nitrogen inflow and outflow of the wetland system.

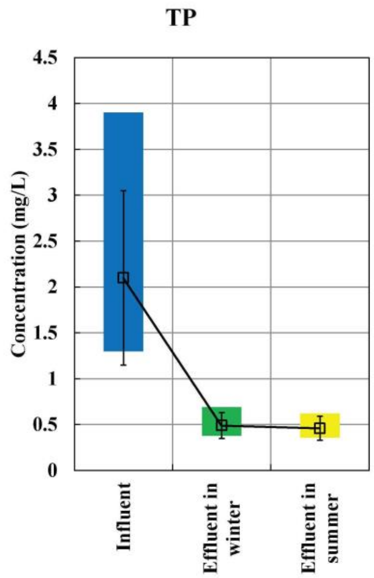

Fig. 5. Concentrations over the winter and summer of the Total Phosphorus inflow and outflow of the wetland system.

CONCLUSION

A novel compound double-layer subsurface flow constructed wetland system has been developed and a full-scale test trial of this system was used in advanced sewage treatment in the northeast of China. The design of the double-layer constructed wetland with an insulating surface materials cover filling and a high-efficiency compound substrate applying the bio-augmentation technology, the operational stability of the CWSs have been improved effectively, while in use through the freezing winter. The novel double-layer subsurface flow constructed wetland system maintained a high purification capacity for the organic contaminants at low temperatures. There was a relatively low removal rate of the ammonia in the system during the winter because of the limitation of nitrification by the low temperature, but the system had a much better performance in denitrification for nitrate nitrogen removal, where the system average TN removal rate was about 42%. The compounded substrates provide the system with a high performance of TP removal. The results of this full-scale research study can be used for determination of the technologically feasible and applicability of advanced wastewater treatment systems in the northernmost province of China, which was considered unsuitable for using CWSs in the past. The novel structure of CWSs can be used to solve environmental problems caused by decentralized wastewater systems in small towns and the countryside in Northern China.

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