Denitrification process of deep bed denitrification filter for secondary effluent from urban sewage treatment plant

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Abstract. In recent years, the sewage discharge standards are getting stricter, and advanced wastewater treatment is more important. Therefore, further advanced treatment of the effluent from the wastewater treatment plant has become a research hotspot. In this study, deep bed denitrification filter (DBDF) was used to treat secondary effluent from urban sewage treatment plants. The effects of different carbon and nitrogen ratios (C/N) and hydraulic retention time (HRT) on the nitrogen removal efficiency of the system were investigated. The results showed that the optimum C/N of the reactor was 5, and the optimum HRT was 0.5h. After running for 15 days under the optimal conditions, the results showed that DBDF ran stably, and the denitrification effect was good. The average effluent concentrations of COD and TN were 16.4 and 6.9mg/L, and the average removal rates were 77.0% and 57.7% respectively.

1. Introduction

With the development of social economy and the accelerating speed of urbanization [1], the population of villages and towns is continuously intensive. Township and village enterprises are developing rapidly, resulting in the increasing of the wastewater discharge amount [2]. The shortage of water resources and water pollution are seriously aggravated, among which eutrophication [3] has become a major problem affecting the water environment. Nitrogen and phosphorus are one of the main factors that cause water eutrophication. So the emission standards of nitrogen and phosphorus are increasingly strict.

To meet the “discharge standards of pollutants for municipal wastewater treatment plant” (DB 12/599-2015), the existing urban sewage treatment plants need to significantly improve nitrogen and phosphorus removal capacity. The upgrading measures should be taken to deal with the existing problems [4]. The traditional advanced treatment process (coagulation + precipitation + filtration) has a higher removal rate of phosphorus [5], but the removal or reduction of the concentration of nitrate nitrogen in the secondary effluent is incapable, resulting in a limited removal rate of TN. Using denitrifying bacteria in the denitrification filter to remove nitrate nitrogen is an effective way to reduce the TN concentration in the secondary effluent of urban sewage treatment plants [6]. The deep bed denitrification filter has a good denitrification effect [7], so it has become a hot spot in the research and application of urban sewage advanced treatment. This study provides technical support for solving the problem of total nitrogen compliance in the existing sewage treatment process by studying the deep bed denitrification filter.
2. Material and Methods

2.1. Influent and effluent quality
The inlet and outlet water indicators are shown in Table 1. The secondary effluent from a sewage treatment plant in Tianjin was used as the experimental influent, which met the national "urban sewage treatment plant pollutant discharge standard" (GB 18918-2002), level of B standard. The effluent should meet “discharge standards of pollutants for municipal wastewater treatment plant” (DB 12/599-2015), level of A standard.

Table 1. Standard for design of influent and effluent

| Water quality index | COD (mg/L) | TN (mg/L) | TP (mg/L) |
|---------------------|------------|-----------|-----------|
| Influent            | ≤ 60       | ≤ 20      | ≤ 1       |
| Effluent            | ≤ 30       | ≤ 20      | ≤ 0.3     |

2.2 Laboratory-scale deep bed denitrification filter (DBDF) system
The experimental system is shown in Figure 1. The DBDF was a plexiglass tube with an inner diameter of 110 mm and a column height of 900 mm. The height of the support layer and filling layer were 100 mm and 600 mm, respectively. The water flow in the filter was downflow. There were 5 sampling ports with a sampling interval of 10 cm. There was a backwashing port and a water inlet at the bottom, and a water outlet at the top. The supporting layer consisted of pebbles with a diameter of 5-10 mm, and the filling layer consisted of quartz sand with a diameter of 3-5 mm.

2.3 Wastewater quality analysis
Detection indicators of influent and effluent water samples were as follows: chemical oxygen demand (COD), nitrate nitrogen (NO$_3$-N), nitrite nitrogen (NO$_2$-N) and total nitrogen (TN). Parameters were measured according to the standard methods for the Examination of Water and Wastewater (APHA 2012). Dissolved oxygen (DO) concentration was detected by a dissolved oxygen meter (HQ30d).

3. Results and discussion

3.1 Effect of different C/N
In this study, the influent concentration of NO$_3^-$-N ranged from 11.9 to 14.0 mg/L, and the hydraulic retention time of DBDF was 0.5 h. By adding sodium acetate, C/N was adjusted to 3, 4, 5 and 6, respectively. Under different C/N conditions, the effect of DBDF on COD removal and denitrification effect were studied. The optimal C/N was obtained through analysis.

### 3.1.1 Removal of COD
As shown in Figure 2, DBDF had a good removal efficiency on COD under different C/N conditions, and the removal rates were all above 70%. When C/N was adjusted to 3, 4 and 5, the average removal rates of COD were 71.7%, 77.6% and 83.7%, respectively. The COD concentrations of the effluent remained at a low level with average values of 10.5, 10.8 and 11.6 mg/L, respectively. When C/N was 6, the average removal rate of COD was 76.1%. The COD concentration of the effluent was increased, and the average value was 18.9 mg/L, which made the effluent water quality worse and caused waste of carbon source [8]. In addition, when the C/N was 6, the growth rate of the biofilm in the reactor was accelerated, leading to premature clogging of the filter material. In order to ensure good processing results, it was necessary to increase the frequency of backwashing, which resulted in an increase in the operating costs.

![Fig. 2. Effect of C/N on COD removal](image)

### 3.1.2 Denitrification effect of DBDF
As shown in Figure 3, the average NO$_3^-$-N concentration of the influent was 13.1 mg/L. With the increase of C/N, the removal rate of NO$_3^-$-N gradually increased. When C/N was adjusted to 3, the removal of NO$_3^-$-N was poor because that the carbon source required by microorganisms was insufficient. The average removal rate was only 17.7%, and the average NO$_3^-$-N concentration of the effluent was 11.0 mg/L. When C/N was 4, the removal rate of NO$_3^-$-N was obviously improved. The average removal rate was 43.5%, and the NO$_3^-$-N concentration of the effluent was about 7 mg/L. When C/N increased to 5, the carbon source in the system was sufficient, so the NO$_3^-$-N removal rate increased to 59.4%, and the NO$_3^-$-N concentration of the effluent decreased to 5.2 mg/L. When C/N was further increased to 6, the average NO$_3^-$-N concentration of the effluent was reduced to 2.8 mg/L, and the average removal rate was 79.1%.
As shown in Figure 4, when C/N was adjusted to 3, the conversion rate of NO₃⁻-N to NO₂⁻-N was slow due to insufficient carbon source [9], and the accumulation of NO₂⁻-N reached 1.03 mg/L. When C/N was 4, the accumulated value of NO₂⁻-N reached the maximum. Because the COD concentration in the reactor was higher, the conversion rate of NO₃⁻-N to NO₂⁻-N increased. When C/N was increased to 5, since there was enough carbon source, it can ensure NO₂⁻-N was converted into N₂, and the NO₂⁻-N accumulation value dropped rapidly to 0.33 mg/L. When C/N increased to 6, the average cumulative concentration of NO₂⁻-N was 0.05 mg/L, and there was almost no accumulation of NO₂⁻-N.

3.2 Effect of HRT
In this study, the influent NO₃⁻-N concentration ranged from 12.6 to 13.9 mg/L, and the C/N was 5. HRT of DBDF was set at 0.25, 0.5, 0.75 and 1 h, respectively. The effect of DBDF on COD removal and denitrification effect under different HRT conditions were studied.

3.2.1 Removal of COD
As shown in Figure 5. When the HRT was adjusted to 0.25 h, the COD removal effect was poor. The average removal rate was 66.7%, and the effluent COD concentration was more than 20 mg/L, indicating that the biofilm and sewage contact time was insufficient, so the carbon source was not fully utilized [10]. Part of the carbon source was discharged with the water flow, resulting in a higher COD effluent concentration. When the HRT was 0.5 h, the biofilm has enough contact time with the carbon source in the sewage, which was beneficial for denitrification. The organic matter could be fully utilized by the microorganisms, and the COD removal rate was increased to 80.3%. When the HRT was 0.75 h, the removal rate of COD increased slightly. When the HRT was further extended to 1 h, the COD concentration of the effluent didn’t decrease significantly. The reason might be that the secondary effluent contained a small amount of refractory COD, which was difficult to remove [11].
3.2.2 Denitrification effect of DBDF

As shown in Figure 6, when the HRT was 0.25 h, the average NO$_3^-$-N concentration of the effluent was 6.7 mg/L, and the average removal rate was only 48.3%. The short hydraulic retention time led to insufficient contact time between microorganisms and pollutants, so the removal effect was poor. When the HRT was 0.5 h, the sewage had sufficient residence time in the system, so that the removal rate of NO$_3^-$-N increased to 69.9%. When the HRT was 0.75 h, the removal rate of NO$_3^-$-N increased slightly. When HRT was further extended to 1 h, the removal rate of NO$_3^-$-N decreased to 63.4% instead. The reason was that the excessive HRT led to low organic load. The carbon source in the filter column couldn’t be used sufficiently, which was not conducive to the growth of the biofilm.

As shown in Figure 7, when the HRT was adjusted to 0.25, 0.5, 0.75 and 1 h, the average NO$_2^-$-N effluent concentrations of DBDF were 2.04, 0.21, 0.04 and 0.03 mg/L, respectively. It showed that the residence time of sewage in the system was too short when HRT was 0.25 h. Although most of the NO$_3^-$-N has been converted into NO$_2^-$-N, NO$_2^-$-N was not completely converted into N$_2$, which made the NO$_2^-$-N accumulation value in the effluent reach 2.04 mg/L. When HRT was 0.5, 0.75 and 1 h, with the prolongation of the residence time of sewage in the system, the degradation of pollutants became more and more sufficient, and there was enough time to convert NO$_2^-$-N into N$_2$. So the effluent concentration was rapidly reduced. The effluent was substantially free of NO$_2^-$-N accumulation.
3.3 Continuous operation of DBDF

The DBDF was run under the optimal conditions determined by the above studies. The operating conditions of DBDF were as follows: C/N was 5 and HRT was 0.5 h. Figure 8 showed the removal effect of COD. The COD concentration of the influent ranged from 66.7 to 75.7 mg/L, and the COD concentration effluent ranged from 14.1 to 19.0 mg/L. The average removal rate was 77.0%. The removal rate of TN was shown in Figure 8. During the operation, the TN concentration of the influent ranged from 14.9 to 17.6 mg/L. The average TN concentration of effluent was 6.9 mg/L, which varied from 5.2 to 7.9 mg/L, which could meet “discharge standards of pollutants for municipal wastewater treatment plant” (DB 12/599-2015), level of A standard. The average removal rate of TN was 57.7%. The study proved that the DBDF had a good nitrogen removal efficiency.
4. Conclusion

1) The DBDF in this experiment showed very good nitrogen and COD removal performance (TN removal > 58%, NO3-N removal > 90%, and COD removal > 70%). The effluent could meet “discharge standards of pollutants for municipal wastewater treatment plant” (DB 12/599-2015), level of A standard.

2) The system examined the impact of C/N and HRT on the result of nitrogen removal. The results showed that the system had a good removal efficiency on COD and TN when C/N and HRT were adjusted to 5 and 0.5 h respectively.

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