SEASONAL PERFORMANCE OF SEQUENCING BATCH BIOFILM REACTORS AND ECOSYSTEM SEWAGE TREATMENT HYBRID PROCESSES IN SMALL TOWNS OF THE THREE GORGES RESERVOIR AREA IN CHINA

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ABSTRACT

This study aimed to address the problems of small towns, e.g. low economy, undeveloped technology and management level, and fluctuant water quality and water quantity. To develop an efficient low-cost small-town sewage treatment technology, the integration of sequencing batch type bioreactor/ecosystem hybrid treatment process was chosen. In this experiment, the bioreactor unit of the process included a sequencing batch biofilm reactor (SBBR), while the ecosystem unit applied a sequencing constructed wetland (SCW) based on a polyurethane foam filler in a matrix. By changing the operation model, tests were carried out to find the key parameters of the optimal operation model for the sequencing batch type bioreactor/ecosystem hybrid treatment process in different seasons. The experiment was conducted throughout a year of operation after setup. The results showed that when the bio- and ecosystem reactors ran together in combination at a temperature of 15 °C ~ 25 °C in spring and autumn, The final effluent chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), and total nitrogen (TN) concentrations of the hybrid reactors were 48 mg/L, 7 mg/L, and 16 mg/L, respectively, with a corresponding total removal efficiencies of 86 %, 89 %, and 79 %. When the ecosystem reactors ran independently in the temperature range of 25 °C ~ 35 °C in the summer, the effluent COD, NH_4^+-N, and TN concentrations were 47 mg/L, 7.3 mg/L, and 17.3 mg/L respectively, with a corresponding total removal rate of 84 %, 87 %, and 74 %. The bioreactors and ecosystem reactors ran together in combination at 5 °C ~ 15 °C in the winter and the final COD, NH_4^+-N, and TN concentrations of the hybrid reactors effluent were, respectively, 54 mg/L, 11 mg/L, and 18 mg/L, with a corresponding total removal of 86 %, 84 %, and 76 %. The research developed an integration of sequencing batch type bioreactor/ecosystem hybrid treatment process with important realistic significance and practical value. The designed operation models are able to be used in guiding practical engineering.

Biotechnol. & Biotechnol. Eq. 2013, **27**(6), 4276-4283

Keywords: sewage treatment; biology; ecology; nitrogen removal; small town; three gorges reservoir

Introduction

The small towns (population of less than 50 000 citizens) of the Three Gorges Reservoir belong to the subtropical humid monsoon climate, hot in the summer and warm in the winter, with four distinct seasons, a long frost-free period, and abundant rainfall. The annual average temperature is 17.0 °C ~ 18.8 °C and the lowest temperature is 6 °C ~ 9 °C in January. The annual average relative humidity is about 80 %. In the Three Gorges Reservoir area, a lot of small towns are located in the rural-urban continuum near the secondary rivers with vulnerable ecological environment. The urban drainage system is unsound; sewage and even part of the overland runoff sewage mixed with municipal industrial waste are often discharged into the local river. This results in polluting the surrounding farmland and even the water supply heavily, increasing the pollution load of secondary rivers, and, eventually, serious deterioration of water quality in the Three Gorges Reservoir area. As the basic factor for the Chongqing urban life pollution, the impact of the sewage from the small towns in the Three Gorges Reservoir area on the environment will become increasingly prominent, which will threaten the course of the Three Gorges Engineering Project. That is why, it is necessary to develop suitable processes for small-town sewage treatment to effective control of small-town sewage, thereby protecting the water environment of the Three Gorges Reservoir.

The quality and quantity of wastewater from small towns are characterized by wild fluctuation. Highly concentrated sewage treated by ecosystem processes typically results in poor and unsteady effluent quality (17). In the case of increasingly scarce land resources, using single ecosystem treatment for small-town sewerage also presents problems such as large area coverage, poor capability of resisting to the impact load, and unstable effluent water quality (9, 14, 22, 28). In addition, the effect of the ecosystem method for wastewater treatment is reduced in autumn and winter because of the low temperatures (13). Therefore, it is inappropriate to treat sewerage with an ecosystem process only. On the other hand, operating a biorector system independently in small-town wastewater treatment is of high investment, large operation cost, and difficult operation and management technology (18).

Bioreactor/ecosystem hybrid treatment technology has been put forward for small-town wastewater treatment processes with high efficiency, low consumption, strong ability of resisting shock loading, and convenient operation and management (4, 10, 19). After effectively reducing the chemical oxygen demand (COD), suspended solids, nitrogen and phosphorus in wastewater by a bioreactor treatment process (2, 6, 16), and further removal of remaining nitrogen and phosphorus by a constructed wetland system, the whole system has been optimized for attaining better effluent water quality (8, 21, 24).

To treat small-town municipal wastewater, different bioreactor/ecosystem hybrid treatment processes have been investigated in China and abroad. For example, Vera et al. (23) described and characterized the performance of 11 wastewater treatment plants (WWTPs) with secondary horizontal subsurface flow (HSSF) constructed wetland systems. Hybrid systems based on an up-flow anaerobic sludge blanket (UASB) reactor have been constructed in combination with vertical and horizontal flow constructed wetlands (12) or with free water surface and subsurface flow constructed wetlands (7). Zhang et al. (26) used a bioreactor/ecosystem hybrid process in which the bioreactor unit was a continuous-flow integrative biological reactor (CIBR) and the ecosystem unit was a wavy subsurface-flow constructed wetland. Chen et al. (5) designed an optimal combinative process of bioreactor and ecosystem treatment to treat the municipal wastewater in south China cities. According to the features of the municipal wastewater and unit technology, various kinds of substrate loads are distributed between the two treatment stages. The advantages of flexibility and high efficiency of the bioreactor treatment are optimally combined with those of low-cost consumption and stability of ecosystem treatment. The main effluent quality indexes can reach grade IV of the environmental quality standards for surface water in China (5).

Above all, processes with high efficiency, low consumption and stable effluent are always the improvement endpoint in small-town wastewater treatment. Bioreactor/ecosystem synergy processes combine bioreactor and ecosystem-based technology to fully make use of their respective advantages. Therefore, in this paper, an integration of sequencing batch type bioreactor/ecosystem hybrid treatment process is applied to small-town sewage treatment, aiming at exploring small-town wastewater treatment processes with high efficiency, low consumption, strong ability of resisting shock loading, and convenient operation and management. In the analysis of the bioreactor/ecosystem hybrid treatment process, the key points are the load distribution in the two units and the energy consumption situation of the hybrid reactors. Since the high efficiency typical of bioreactor treatment and the low consumption characteristic of ecosystem treatment are both fully expressed in the process, the hybrid treatment technology can be reasonably optimized under different conditions, and is able to finally achieve a stable treatment effect as well as cost saving.

To clearly perform the function of each unit and to reaching the best overall efficiency, the bioreactor and ecosystem processes need to be precisely and mutually coordinated for removing contaminants under regulation and control. Thus, the hybrid technology could operate flexibly, being able to utilize the efficiency of each unit and distribute the COD, N, and P loads reasonably. By changing the hybrid process operating conditions, the performance of the bioreactor/ecosystem hybrid process for small-town sewage was studied.

Materials and Methods

Experiment setting

The full-scale hybrid reactors were constituted by bioreactors and two-stage ecosystem reactors, mainly to study the working condition of the bioreactor/ecosystem hybrid technology. The bioreactors were sequencing batch biofilm reactors (SBBR). Spherical polyurethane foam was used as the biomass carrier and the packing rate was 70 % (V/V). The seed sludge was dewatered sludge from a wastewater treatment plant in the local small towns. The ecosystem reactors were designed as a sequencing constructed wetland (SCW). In order to improve their effectiveness, designed sewage treatment experiments were carried out by introducing five species of wetland plants into the SCW, such as canna, reed, *Acorus calamus*, *Cyperus slternifolius* and *Typha latifolia*. The configuration and flow chart of the hybrid reactors are illustrated in **Fig. 1**.

Water quality

The quality of the influent in different seasons is given in **Table 1**.

TABLE 1

Quality of wastewater in the experiment

Seasons	COD (mg/L)	NH_4^+-N (mg/L)	TN (mg/L)	PO_4^{3}-P (mg/L)	pH
Spring and autumn	320~380	55~75	65~91	1.5~3.5	7.3~8.3
Summer	260~340	50~60	60~72	1.2~2.8	7.3~8.3
Winter	310~450	58~78	66~86	1.8~3.0	7.3~8.3

Experimental procedure

In this experiment, an SBBR and a two-stage SCW series were applied in bioreactors and ecosystem reactors, respectively. Running at the lowest operating cost, the experiment studied the treatment efficiency of three different operating conditions, and finally obtained the optimal operating conditions for each season. Four bioreactors operated independently and intermittently, 45 % full of spherical combined packing, with a drainage ratio of 0.7, and dissolved oxygen (DO) concentration of 5 mg/L in each reactor; while 70 % spherical polyurethane foam packing was filled in each ecosystem SCW reactor. The operating parameters of the reactors in different seasons are given in **Table 2**.

Analyses

Parameters such as effluent chemical oxygen demand (COD), ammonium nitrogen (NH_4^+-N), and total nitrogen (TN) were tested periodically and analyzed according to the standard methods for the Examination of Water and Wastewater published by the American Public Health Association (1).

Results and Discussion

Effects of different operating conditions on reactor effluent in spring and autumn

In spring and autumn, the temperature of the reactors was controlled at 15 °C to 25 °C. The effects of different operating

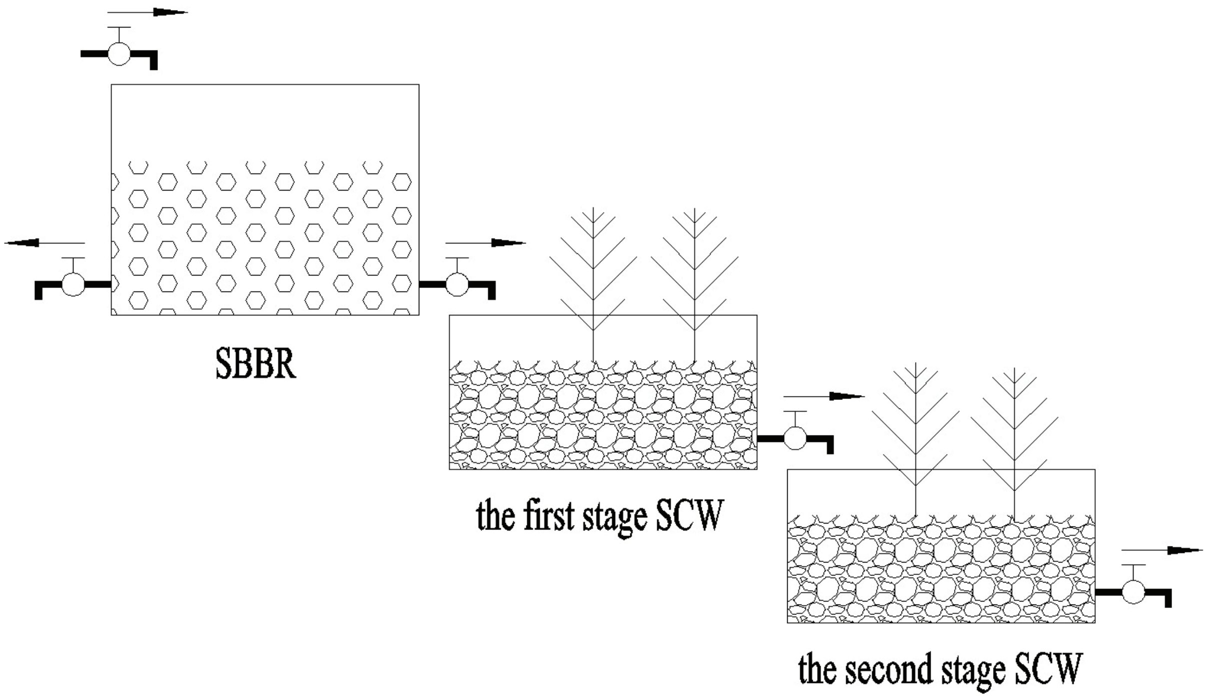

Fig. 1. Experimental equipment schematic diagram of bioreactor (sequencing batch biofilm reactor, SBBR) and ecosystem (sequencing constructed wetland, SCW) synergies.

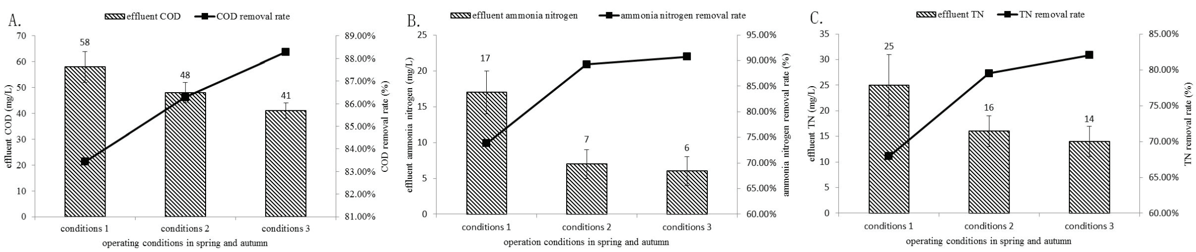

Fig. 2. Effects of different operating conditions on reactor effluent in spring and autumn: COD (**A**); NH_4^+-N (**B**); TN (**C**).

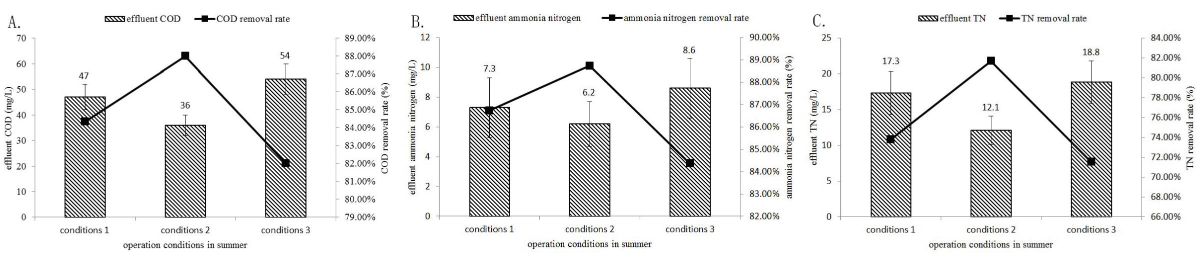

Fig. 3. Effects of different operating conditions on reactor effluent in summer: COD (**A**); NH_4^+-N (**B**); TN (**C**).

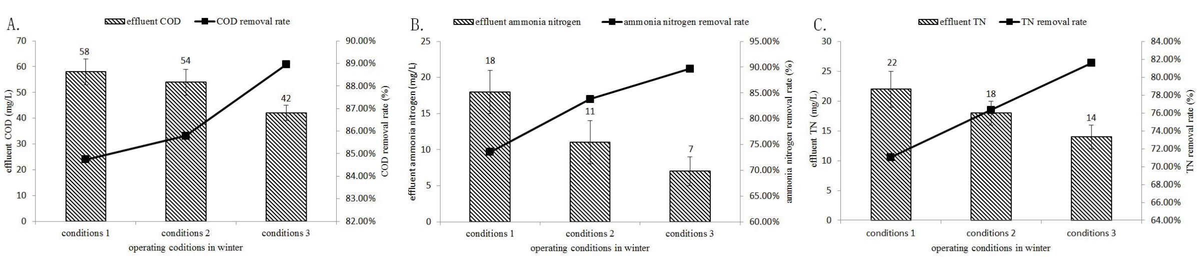

Fig. 4. Effects of different operating conditions on reactor effluent in winter: COD (**A**); NH_4^+-N (**B**); TN (**C**).

TABLE 2

Operating parameters of reactors in different seasons

<table>
<tr><th>Seasons</th><th>Reactors</th><th>Stage</th><th>Unit</th><th>Condition 1</th><th>Condition 2</th><th>Condition 3</th></tr>
<tr><td rowspan="12">Spring and autumn</td><td rowspan="4">Bioreactor</td><td>Inflow time</td><td rowspan="4">h</td><td>—</td><td>0.3</td><td>0.3</td></tr>
<tr><td>Aeration time</td><td>0</td><td>1</td><td>2</td></tr>
<tr><td>Sedimentation time</td><td>—</td><td>0.5</td><td>0.5</td></tr>
<tr><td>Outflow time</td><td>—</td><td>0.3</td><td>0.3</td></tr>
<tr><td rowspan="4">Ecosystem reactor SCW1</td><td>Inflow time</td><td rowspan="4">h</td><td colspan="3">0.3</td></tr>
<tr><td>Reaction time</td><td colspan="3">16</td></tr>
<tr><td>Outflow time</td><td colspan="3">0.3</td></tr>
<tr><td>Idle time</td><td colspan="3">4</td></tr>
<tr><td rowspan="4">Ecosystem reactor SCW2</td><td>Inflow time</td><td rowspan="4">h</td><td colspan="3">0.3</td></tr>
<tr><td>Reaction time</td><td colspan="3">12</td></tr>
<tr><td>Outflow time</td><td colspan="3">0.3</td></tr>
<tr><td>Idle time</td><td colspan="3">4</td></tr>
<tr><td rowspan="12">Summer</td><td rowspan="4">Bioreactor</td><td>Inflow time</td><td rowspan="4">h</td><td>—</td><td>0.3</td><td>0.3</td></tr>
<tr><td>Aeration time</td><td>0</td><td>1</td><td>1</td></tr>
<tr><td>Sediment time</td><td>—</td><td>0.5</td><td>0.5</td></tr>
<tr><td>Outflow time</td><td>—</td><td>0.3</td><td>0.3</td></tr>
<tr><td rowspan="4">Ecosystem reactor SCW1</td><td>Inflow time</td><td rowspan="4">h</td><td colspan="3">0.3</td></tr>
<tr><td>Reaction time</td><td colspan="3">16</td></tr>
<tr><td>Outflow time</td><td colspan="3">0.3</td></tr>
<tr><td>Idle time</td><td colspan="3">4</td></tr>
<tr><td rowspan="4">Ecosystem reactor SCW2</td><td>Inflow time</td><td rowspan="4">h</td><td>0.3</td><td>0.3</td><td>—</td></tr>
<tr><td>Reaction time</td><td>12</td><td>12</td><td>0</td></tr>
<tr><td>Outflow time</td><td>0.3</td><td>0.3</td><td>—</td></tr>
<tr><td>Idle time</td><td>4</td><td>4</td><td>0</td></tr>
<tr><td rowspan="12">Winter</td><td rowspan="4">Bioreactor</td><td>Inflow time</td><td rowspan="4">h</td><td rowspan="4">1</td><td>0.3</td><td rowspan="4">3</td></tr>
<tr><td>Aeration time</td><td>2</td></tr>
<tr><td>Sediment time</td><td>0.5</td></tr>
<tr><td>Outflow time</td><td>0.3</td></tr>
<tr><td rowspan="4">Ecosystem reactor SCW1</td><td>Inflow time</td><td rowspan="4">h</td><td colspan="3">0.3</td></tr>
<tr><td>Reaction time</td><td colspan="3">16</td></tr>
<tr><td>Outflow time</td><td colspan="3">0.3</td></tr>
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<tr><td>Idle time</td><td colspan="3">4</td></tr>
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conditions on the reactor effluent COD, NH_4^+-N, and TN during this period are shown in **Fig. 2**. Under Operating Condition 1, the COD, NH_4^+-N and TN loads in the bioreactor were 0. The removal loads in the first-stage ecosystem reactor were 70.1 g/(m^2·d) for COD, 11.3 g/(m^2·d) for NH_4^+-N, and 12.7 g/(m^2·d) for TN, respectively. The effluent COD, NH_4^+-N and TN content were respectively 146 mg/L, 32 mg/L, and 41 mg/L, with corresponding removal of 58 %, 51 %, and 47 %. The removal loads in the second-stage ecosystem reactor were 40.3 g/(m^2·d) for COD, 6.9 g/(m^2·d) for NH_4^+-N, and 7.3 g/(m^2·d) for TN, respectively. The effluent COD, NH_4^+-N and TN content were respectively 58 mg/L, 17 mg/L, and 25 mg/L, with total removal of 60 %, 47 %, and 39 %, respectively. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 58 mg/L, 17 mg/L and 25 mg/L, respectively, with corresponding total removal of 83 %, 74 %, and 68 %. The final effluent COD content from the hybrid reactors could meet the primary standard B of discharge standard of pollutants for municipal wastewater treatment plants in China, and both NH_4^+-N and TN content satisfied the secondary standard.

Under Operating Condition 2, the COD, NH_4^+-N and TN loads in the bioreactor were 1.95 kg/(m^3·d), 0.34 kg/(m^3·d), and 0.30 kg/(m^3·d), respectively. The corresponding effluent content was 234 mg/L, 45 mg/L, and 60 mg/L, with total removal of 33 %, 31 %, and 23 %, respectively. The removal loads in the first-stage ecosystem reactor were 50.2 g/(m^2·d) for COD, 9.6 g/(m^2·d) for NH_4^+-N, and 10.7 g/(m^2·d) for TN, respectively. The corresponding effluent content was 88 mg/L, 17 mg/L, and 29 mg/L, with total removal of 62 %, 62 %, and 52 % for each index. The removal loads in the second-stage ecosystem reactor were 18.3 g/(m^2·d) for COD, 4.6 g/(m^2·d) for NH_4^+-N, and 6.0 g/(m^2·d) for TN, respectively. The effluent COD, NH_4^+-N and TN content was, respectively, 48 mg/L, 7 mg/L, and 16 mg/L, with total removal of 45 %, 59 %, and 45 % for each index. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 48 mg/L, 7 mg/L, and 16 mg/L, respectively, with corresponding total removal of 86 %, 89 %, and 79 %. The final effluent COD content from the hybrid reactors met the primary standard A of discharge standard of pollutants for municipal wastewater treatment plants in China, and both NH_4^+-N and TN content satisfied the primary standard B.

Under Operating Condition 3, the COD, NH_4^+-N and TN loads in the bioreactor were 1.61 kg/(m^3·d), 0.26 kg/(m^3·d), and 0.22 kg/(m^3·d), respectively. The corresponding effluent content was 158 mg/L, 34 mg/L, and 52 mg/L, with total removal of 55 %, 48 %, and 33 %, respectively. The removal loads in the first-stage ecosystem reactor were 34.7 g/(m^2·d) for COD, 7.2 g/(m^2·d) for NH_4^+-N, and 8.9 g/(m^2·d) for TN, respectively. The corresponding effluent content was 57 mg/L, 13 mg/L, and 26 mg/L, with total removal of 64 %, 62 %, 50 % for each index. The removal loads in the second-stage ecosystem reactor were 7.3 g/(m^2·d) for COD, 3.2 g/(m^2·d) for NH_4^+-N, and 5.5 g/(m^2·d) for TN. The effluent COD, NH_4^+-N and TN content was, respectively, 41 mg/L, 6 mg/L, and 14 mg/L, with total removal of 28 %, 54 %, and 46 % for each index. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 41 mg/L, 6 mg/L, and 14 mg/L, respectively, with corresponding total removal of 88 %, 91 %, and 82 %. The final effluent COD and TN content from the hybrid reactors could both meet the primary standard A of discharge standard of pollutants for municipal wastewater treatment plant in China, and the NH_4^+-N content satisfied the primary standard B.

In spring and autumn, the experiment temperature was controlled at 15 °C to 25 °C, and the hydraulic retention time (HRT) in the bioreactors was 0 h, 1 h, and 2 h in condition 1, 2, and 3, respectively. The quality of hybrid reactors effluent was better, as the HRT was longer (**Fig. 2**): the COD total removal in Condition 2 and 3 was 3 % and 5 % higher than the 83 % in Condition 1; the NH_4^+-N total removal in Condition 2 and 3 was 15 % and 17 % higher than the 74 % in Condition 1; the TN total removal in condition 2 and 3 was 11 % and 14 % higher than the 68 % in Condition 1. The hybrid reactors achieved relatively steady removal of COD in all the three conditions. Even when the HRT was 0 under Condition 1, the final COD concentration in the hybrid reactors outflow could still satisfy the primary standard B. The relatively high temperature in the spring and autumn and the idle period set in the ecosystem reactors all successfully helped to improve the DO concentration in the wetlands and ultimately increased the aerobic COD degradation in the system. However, the nitrogen removal under Condition 1 was rather poor. The low nitrogen removal in the bioreactors added to the overload on the ecosystem reactors. The load of NH_4^+-N in the first-stage ecosystem reactors was 11.3 g/(m^2·d), or 3~5 times higher than the one in a typical constructed wetland; the load of TN was 12.7 g/(m^2·d), of 4~6 times higher than the normally expected one. The load of NH_4^+-N and TN in the secondary-stage ecosystem reactors was, respectively, 6.9 g/(m^2·d) and 7.3 g/(m^2·d), which were also higher than the normal loads (11). Meanwhile, the relatively low temperature in spring and autumn led to low activity of the microorganisms and an overall imperfect treatment efficiency (25). For these reasons the bioreactors could not work well under Condition 1, resulting in difficulty to meet the standard in whole.

Under Condition 2, the HRT in the bioreactors was controlled at 1 h. Compared to Condition 1, the efficiency of nitrogen removal rose and the NH_4^+-N and TN concentration in the final effluent could satisfy the primary standard B. In this case, the ecosystem reactors covered an area of 4.5 m^2 per cubic meter of treated wastewater. Under Condition 3, the HRT in the bioreactors was controlled at 2 h. Compared to Condition 1, the efficiency of nitrogen removal rose more than that in Condition 2, and the TN and NH_4^+-N concentration in the final effluent could, respectively, satisfy the primary standard A and primary standard B. In this case, the ecosystem reactors covered an area of 3.3 m^2 per cubic meter of treated wastewater.

Comparing to Condition 2, the HRT was longer, and the degradation capacity of COD, NH_4^+-N, and TN was respectively 76 mg/L, 11 mg/L, and 8 mg/L more in the bioreactors under Condition 3. The lower loads in the effluent of the bioreactors resulted in a better final effluent than the one under Condition 2. Since the COD, NH_4^+-N and TN content in the final effluent in Condition 2 could meet the primary standard B, considering economy of energy consumption, Condition 2 could be chosen as the optimal operating condition in spring and autumn.

Effects of different operating conditions on reactor effluent in summer

In the summer, the temperature of the reactors was controlled at 25 °C to 35 °C. The effects of the operating conditions on the reactor effluent COD, NH_4^+-N, and TN during this period are shown in **Fig. 3**. Under Operating Condition 1, the COD, NH_4^+-N and TN loads in the bioreactor were 0. The removal loads in the first-stage ecosystem reactor were 59.8 g/(m^2·d) for COD, 10.2 g/(m^2·d) for NH_4^+-N, and 9.8 g/(m^2·d) for TN. The effluent COD, NH_4^+-N and TN content was respectively 126 mg/L, 25.4 mg/L, and 37.4 mg/L, with corresponding removal of 58 %, 54 %, and 43 %. The removal loads in the second-stage ecosystem reactor were 36.2 g/(m^2·d) for COD, 8.3 g/(m^2·d) for NH_4^+-N, and 9.2 g/(m^2·d) for TN. The effluent

COD, NH_4^+-N and TN content was, respectively, 47 mg/L, 7.3 mg/L, and 17.3 mg/L, with total removal of 63 %, 71 %, and 54 %, respectively. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 47 mg/L, 7.3 mg/L, and 17.3 mg/L, respectively, with corresponding total removal of 84 %, 87 %, and 74 %. The final effluent COD content from the hybrid reactors could meet the primary standard A of discharge standard of pollutants for municipal wastewater treatment plants in China, and both NH_4^+-N and TN content satisfied the primary standard B.

Under Operating Condition 2, the COD, NH_4^+-N and TN loads in the bioreactor were 2.05 kg/(m^3·d), 0.40 kg/(m^3·d), and 0.30 kg/(m^3·d), respectively. The corresponding effluent content was 178 mg/L, 31 mg/L, and 48 mg/L, with total removal of 41 %, 44 %, and 27 %, respectively. The removal loads in the first-stage ecosystem reactor were 42.6 g/(m^2·d) for COD, 7.7g/(m^2·d) for NH_4^+-N, and 10.0 g/(m^2·d) for TN. The corresponding effluent content was 54 mg/L, 8.6 mg/L, and 18.8 mg/L, with total removal of 70 %, 72 %, and 61 % for each index. The removal loads in the second-stage ecosystem reactor were 8.3 g/(m^2·d) for COD, 1.1 g/(m^2·d) for NH_4^+-N, and 3.1 g/(m^2·d) for TN, respectively. The effluent COD, NH_4^+-N and TN content was, respectively, 36 mg/L, 6.2 mg/L, and 12.1 mg/L, with total removal of 33 %, 28 %, and 36 % for each index. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 36 mg/L, 6.2 mg/L, and 12.1 mg/L, respectively, with corresponding total removal of 88 %, 89 %, and 82 %. The final effluent COD and TN content from the hybrid reactors could both meet the primary standard A of discharge standard of pollutants for municipal wastewater treatment plants in China, and the NH_4^+-N content satisfied the Under Operating Condition 3, the COD, NH_4^+-N and TN loads in the bioreactor were 2.05 kg/(m^3·d), 0.40 kg/(m^3·d), and 0.30kg/(m^3·d), respectively. The corresponding effluent content was 178 mg/L, 31 mg/L, and 48 mg/L, with total removal of 41 %, 44 %, and 27 %, respectively. The removal loads in the first-stage ecosystem reactor were 42.6 g/(m^2·d) for COD, 7.7 g/(m^2·d) for NH_4^+-N, and 10.0 g/(m^2·d) for TN, respectively. The corresponding effluent content was 54 mg/L, 8.6 mg/L, and 18.8 mg/L, with total removal of 70 %, 72 %, and 61 % for each index. The removal loads in the second-stage ecosystem reactor were 0. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 54 mg/L, 8.6 mg/L, and 18.8 mg/L, respectively, with corresponding total removal of 82 %, 84 %, and 72 %. The final effluent COD and TN content from the hybrid reactors could both meet the primary standard B of discharge standard of pollutants for municipal wastewater treatment plants in China, and the NH_4^+-N content satisfied the secondary standard.

In the summer, the HRT in the bioreactors was respectively 0 h and 1 h in Condition 1 and 2. The quality of hybrid reactors effluent was better at longer HRT (**Fig. 3**): the COD total removal in Condition 2 was 4 % higher than the 84 % in Condition 1; the NH_4^+-N total removal in Condition 2 was 2 % higher than the 87 % in Condition 1; the total TN removal in Condition 2 was 8 % higher than the 74 % in Condition 1.

The hybrid reactors showed relatively steady removal of COD in both conditions. Even when the HRT of the bioreactors was 0 under Condition 1, the final COD concentration of the hybrid reactors outflow could still satisfy the primary standard A. The relatively high temperatures in the summer led to high microbial activity, and the idle period set in the ecosystem reactors successfully helped to improve the DO concentration in the wetlands and ultimately strengthened the aerobic COD degradation in the system. Under Condition 1, with the ecosystem reactors working in series independently, the system could remove nitrogen efficiently: the nitrifying bacteria in the wetland system showed the strongest activity and the fastest nitration rate in the summer (20); lush plants could absorb part of the available nitrogen, and the roots helped oxygen restoration (15, 27). The idle period set in both stages was able to fulfill the re-aeration requirements, effectively enhancing the activity of heterotrophic aerobic bacteria and nitrifying bacteria. The load of NH_4^+-N in the first-stage ecosystem reactors was 10.2 g/(m^2·d), or 3~5 times higher than the one in a typical constructed wetland; the load of TN was 9.8 g/(m^2·d), of 4~6 times higher than the normal values. The loads of NH_4^+-N and TN in the secondary-stage ecosystem reactors were, respectively, 8.3 g/(m^2·d) and 9.2 g/(m^2·d), which were also higher than the normal loads. Because of the relatively high temperature in the summer, the ecosystem reactors were able to work efficiently in removing nitrogen. In this case, the ecosystem reactors covered an area of 4.6 m^2 per cubic meter of wastewater treated.

Under Condition 2, the HRT in the bioreactors was controlled at 1 h. Because the bioreactor treated a portion of TN under this condition, the COD, NH_4^+-N, and TN content in the ecosystem reactor influent were respectively 178 mg/L, 31 mg/L, and 48 mg/L. Compared to Condition 1, the efficiency of nitrogen removal rose and the NH_4^+-N and TN concentration in the final effluent could respectively satisfy the primary standard A and B. In this case, the ecosystem reactors covered an area of 2.48 m^2 per cubic meter of wastewater treated.

Under Condition 2, the COD, NH4+-N, and TN content in the effluent of the first-stage ecosystem reactors were respectively 54 mg/L, 8.6 mg/L, and 18.8 mg/L. The content of COD and TN in the effluent could meet the primary standard B, while the NH_4^+-N concentration satisfied the secondary standard. The COD, NH_4^+-N, and TN removal loads in the secondary-stage ecosystem reactors were only 8.3 g/(m^2·d), 0.9 g/(m^2·d), and 1.8 g/(m^2·d), respectively, with corresponding degradation of 18 mg/L, 2 mg/L, and 4 mg/L. When the influent nitrogen content was low, the system was able to operate simply without the second-stage ecosystem reactors, the same as the system operating under Condition 3. The COD, NH_4^+-N and TN concentration in the final effluent could all satisfy the primary standard B. In this case, the ecosystem reactors covered an area of 2.24 m^2 per cubic meter of wastewater treated.

Effects of different operating conditions on reactor effluent in winter

In the winter, the temperature of the reactors was controlled at 5 °C to 15 °C. The effects of the operating conditions on the reactor effluent COD, NH_4^+-N, TN during this period are shown in **Fig. 4**. Under Operating Condition 1, the COD, NH_4^+-N and TN loads in the bioreactor were 2.17 kg/(m^3·d), 0.45 kg/(m^3·d), and 0.29 kg/(m^3·d), respectively. The corresponding effluent content was 251 mg/L, 52 mg/L, and 59 mg/L, with total removal of 34 %, 24 %, and 22 %, respectively. The removal loads in the first-stage ecosystem reactor were 40.6 g/(m^2·d) for COD, 7.6 g/(m^2·d) for NH_4^+-N, and 8.6 g/(m^2·d) for TN. The corresponding effluent content was 133 mg/L, 30 mg/L, and 34 mg/L, with total removal of 65 %, 56 %, and 55 % for each index. The removal loads in the second-stage ecosystem reactor were 34.4 g/(m^2·d) for COD, 5.5 g/(m^2·d) for NH_4^+-N, and 5.5 g/(m^2·d) for TN. The effluent COD, NH_4^+-N and TN content was respectively 58 mg/L, 18 mg/L, and 22 mg/L, with total removal of 56 %, 40 %, and 35 % for each index. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 58 mg/L, 18 mg/L, and 22 mg/L, respectively, with corresponding total removal of 85 %, 74 %, and 71 %. The final effluent COD content from the hybrid reactors met the primary standard B of discharge standard of pollutants for municipal wastewater treatment plants in China, and both NH_4^+-N and TN content satisfied the secondary standard.

Under Operating Condition 2, the COD, NH_4^+-N and TN loads in the bioreactor were 1.64 kg/(m^3·d), 0.23 kg/(m^3·d), and 0.23 kg/(m^3·d), respectively. The corresponding effluent content was 185 mg/L, 41 mg/L, and 48 mg/L, with total removal of 51 %, 40 %, and 36 %, respectively. The removal loads in the first-stage ecosystem reactor were 31.3 g/(m^2·d) for COD, 7.2 g/(m^2·d) for NH_4^+-N, and 7.9 g/(m^2·d) for TN. The corresponding effluent content was 94 mg/L, 20 mg/L, and 26 mg/L, with total removal of 49 %, 51 %, and 47 % for each index. The removal loads in the second-stage ecosystem reactor were 18.3 g/(m^2·d) for COD, 4.1 g/(m^2·d) for NH_4^+-N, and 3.7 g/(m^2·d) for TN. The effluent COD, NH_4^+-N and TN content was, respectively, 54 mg/L, 11 mg/L, and 18 mg/L, with total removal of 43 %, 45 %, and 31 % for each index. The COD, NH_4^+-N and TN content in the hybrid reactors effluent was 54 mg/L, 11 mg/L, and 18 mg/L, respectively, with corresponding total removal of 86 %, 84 %, and 76 %. The final effluent COD, TN and NH_4^+-N content from the hybrid reactors could all meet the primary standard B of discharge standard of pollutants for municipal wastewater treatment plants in China.

In the winter, the experiment temperature was controlled at 5 °C to 15 °C, and the HRT in the bioreactors was, respectively, 1 h, 2 h, and 3 h in Condition 1, 2, and 3. The quality of hybrid reactors effluent was better when the removal load was lower (**Fig. 4**): the COD total removal in Condition 2 and 3 was 1 % and 4 % higher than the 85 % in Condition 1; the NH_4^+-N total removal in Condition 2 and 3 was 10 % and 16 % higher than the 74 % in Condition 1; the TN total removal in Condition 2 and 3 was 5 % and 11 % higher than the 71 % in Condition 1.

The hybrid reactors achieved relatively steady removal of COD in all the three conditions. Even when the HRT was 1 under Condition 1, the final COD concentration of the hybrid reactors outflow could still satisfy the primary standard B. The relatively low temperatures in the winter did not affect the COD removal in the bioreactors and the idle period set in the ecosystem reactors strengthened the aerobic COD degradation in the system. However, the nitrogen removal under Condition 1 was rather poor. This could be attributed to the low nitrobacterium activity in the ecosystem reactors, resulting from the relatively low temperature in the winter (3), and the short HRT and overload in the bioreactors, which all led to the difficulty in meeting the standard in whole.

Under Condition 2, the HRT in the bioreactors was controlled at 2 h. The NH_4^+-N and TN concentration in the final effluent could both satisfy the primary standard B. In this case, the ecosystem reactors covered an area of 4.7 m^2 per cubic meter of wastewater treated. Under Condition 3, the HRT in the bioreactors was controlled at 3 h. The NH_4^+-N and TN concentration in the final effluent could, respectively, satisfy the primary standard A and B. In this case, the ecosystem reactors covered an area of 3.5 m^2 per cubic meter of wastewater treated.

Comparing to Condition 2, the HRT was longer and the degradation capacity of COD, NH_4^+-N, and TN was respectively 70 mg/L, 11 mg/L, and 8 mg/L higher in the bioreactors under Condition 3. The lower loads in the effluent of the bioreactors resulted in better final effluent than the one under Condition 2. However, since the COD, NH_4^+-N and TN content in the final effluent in Condition 2 could meet the primary standard B, with the consideration of saving energy consumption, Condition 2 could be proposed as the optimal operating condition in winter.

In light of the obtained results, for wastewater treatment in small towns, the optimal operation model for a sequencing batch type bioreactor/ecosystem hybrid treatment process in different seasons should be determined after a small experiment or a pilot test. The performance of other types of hybrid processes for treatment of municipal waters in small towns has also shown promising results. A study covering 11 wastewater treatment plants (WWTPs) with secondary horizontal subsurface flow (HSSF) constructed wetland systems demonstrated good performance after an initial operating period of 8 years (23): mean biochemical oxygen demand (BOD_5) below 25 mg/L in 9 of the 11 plants and removal efficiency for total suspended solids (TSS) between 78 % and 96 %, for total nitrogen (TN) between 48 % and 66 %, and for total phosphorus (TP) from 39 % to 58 %. Green et al. (12) used a hybrid system consisting of an up-flow anaerobic sludge blanket (UASB) reactor and vertical and horizontal flow constructed wetlands to treat the municipal wastewater from a local town after primary sedimentation. The yearly average COD, BOD, and TSS removal efficiencies were higher than 90 %, with effluent BOD and TSS concentrations always less than 20 mg/L. The average effluent concentrations of the hybrid system contained 100 mg/L ± 29 mg/L COD, 11 mg/L ± 5 mg/L BOD, and 11 mg/L ± 7 mg/L TSS (12). El-Khateeb et al. (7) used a treatment train consisting of an USAB reactor followed by free water surface and subsurface flow constructed wetlands for treating municipal wastewater through a connection from the sewerage system. The organic loading rate ranged from 8.5 g/(m^2·d) to 15.2 g/(m^2·d) for COD. COD, BOD and TSS reduction in the hybrid system ranged from 77 % to 92.4 %, 84 % to 99 % and 90 % to 98 % with mean values of 85.3 %, 90.3 % and 95 %, respectively. The average residual levels of COD, BOD and TSS in the final effluent were 21.4 mg/L, 6.4 mg/L, and 2.6 mg/L, respectively (7). Another bioreactor/ecosystem hybrid process combining a continuous-flow integrative biological reactor (CIBR) and a wavy subsurface-flow constructed wetland also gave good effluent quality, which was able to steadily meet the primary standard A of discharge standard of pollutants for municipal wastewater treatment plants in China over a whole year (26).

Comparing to such reports (5, 7, 12, 23, 26), our hybrid system can be considered a more effective and more economical (low cost) small-town sewage treatment technology with higher organic matter and more variation in water quality of the sewage, which was, however, inconvenient for design and management of the leachate treatment technics. Subsequent studies are needed to further optimize the hybrid system.

Conclusions

The bioreactors and ecosystem reactors studied here resulted in an overall COD, NH_4^+-N, and TN total removal efficiency of 84 %, 84 % and 74 %, respectively, during the year of investigation. The final effluent COD, NH_4^+-N, and TN content from the hybrid reactors could meet the primary standard B of discharge standard of pollutants for municipal wastewater treatment plants in China. It was observed that the quality of the final effluent water was related to the operation model of the hybrid reactors. When the bioreactor and ecosystem reactor ran together in combination, the final COD, NH_4^+-N, and TN concentrations of the hybrid reactors effluent in the spring and autumn were 48 mg/L, 7 mg/L, and 16 mg/L, respectively, with corresponding total removal of 86 %, 89 %, and 79 %; and in the winter, 54 mg/L, 11 mg/L, and 18 mg/L, respectively, with corresponding total removal of 86 %, 84 %, and 76 %. When the ecosystem reactors ran independently in the summer, the COD, NH_4^+-N, and TN concentrations of the reactor effluent were, respectively, 47 mg/L, 7.3 mg/L, and 17.3 mg/L, with corresponding total removal efficiencies of 84 %, 87 %, and 74 %. The analysis of the obtained results showed that the optimal operation model (considering the saving of energy consumption) for sequencing batch type bioreactor/ecosystem hybrid treatment process in different seasons is Condition 2 in the spring, autumn and winter, and Operating Condition 1 in the summer.

Acknowledgements

The work reported here was financially supported by the National Key Technology R&D Program of China (2011BAJ07B03).

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