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RESEARCH ARTICLE

Field experiment on biological contact oxidation process to treat polluted river water in the Dianchi Lake watershed

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Abstract In this study two types of biological contact oxidation processes (BCOP), a step-feed (SBCOP) unit and an inter-recycle (IBCOP) unit, were designed to investigate the treatment of heavily polluted river water. The Daqing River, which is the largest pollutant contributor to the Dianchi Lake, one of the most eutrophic freshwater lakes in China, was taken for the case study. It was found that the SBCOP had higher adaptability and better performance in the reduction of COD, TN, and TP, which made it applicable for the treatment of polluted river water entering the Dianchi Lake. Nitrification rate was observed to be greatly affected by the influent temperature. During each season, the nitrification in the SBCOP was higher than that in the IBCOP. TN removal efficiency in the SBCOP was higher than that in the IBCOP during the winter and spring but poorer during the summer, possibly due to the inhibition of denitrification by higher dissolved oxygen level in the summer. Moreover, symbiotic algae-bacteria growth may be conducive to the removal of pollutants.

Keywords step-feed biological contact oxidation process (SBCOP), inter-recycle biological contact oxidation process (IBCOP), river water, removal efficiency, nitrogen transformation, the Dianchi Lake watershed

1 Introduction

Rapid economic development and urbanization have brought about serious environmental problems during the recent decades in China. For surface waters, many large rivers have become polluted by ammonia, organic matters, and oil, and even some river branches have fallen into sewer openings [1]. Many lakes have received and accumulated organic matters, nitrogen, and phosphorus nutrients from their input rivers, causing the problem of lake eutrophication.

The Dianchi Lake, located on the Yungui Plateau, southwest of China, is one of the most eutrophic freshwater lakes in the country [2]. According to the investigation on 29 rivers in the Dianchi Lake catchment carried out in 2006, more than 90% of the river channels have become heavily polluted and the quality of the river water declined to the inferior class V. Municipal wastewater contributed 52%–74% of the total input pollution load. In order to control the pollution situation in the Dianchi Lake, a series of countermeasures, including interception of the combined sewer overflows and construction of new wastewater treatment plants have been implemented. Additionally, elimination of pollutants in the riverway has also been proposed.

Naturally, riparian zones possess an unusually diverse array of biological species and environmental processes, acting as buffers for filtering sediment, nutrients, and other contaminants from upland fields [3,4]. However, most riparian zones along the fluvial corridor had been expropriated because of the large population and farmland shortage in China. Under this circumstance, the idea of a bypass purification system was proposed to exert the restoration function of riparian zones. The system was built on the riverbank or in the waste ponds near the river, receiving and treating the diffluent river water, and finally discharging the treated water into the original riverway. A number of technologies of ecological type, such as land treatment system [5], natural or constructed wetland system [6–10] , and oxidation pond system [11], as well as engineering methods, such as nitrification bio-reactor [12], suspended filler moving-bed [13], suspended carrier biofilm reactor [14], fixed-bed biofilm reactor [15], and seepage biological bed [16], were exploited to treat

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polluted river water with huge fluctuation of water quality under the local conditions.

The biological contact oxidation process (BCOP), also called submerged biological filter or contact aeration system, is a hybrid wastewater treatment system, taking the advantages of both activated sludge process and biofilm process, e.g., no bed clogging and sludge bulking. It has been applied to remove organic matter from domestic sewage [17], industrial organic wastewater [18], and polluted water resources [19]. Also, some engineering methods for river water treatment belong to the BCOP in principle except for the use of a suspended filler [13,14] or ceramic media [15]. However, long-term removal efficiencies of nitrogen and phosphorus of a BCOP for river water treatment is seldom studied.

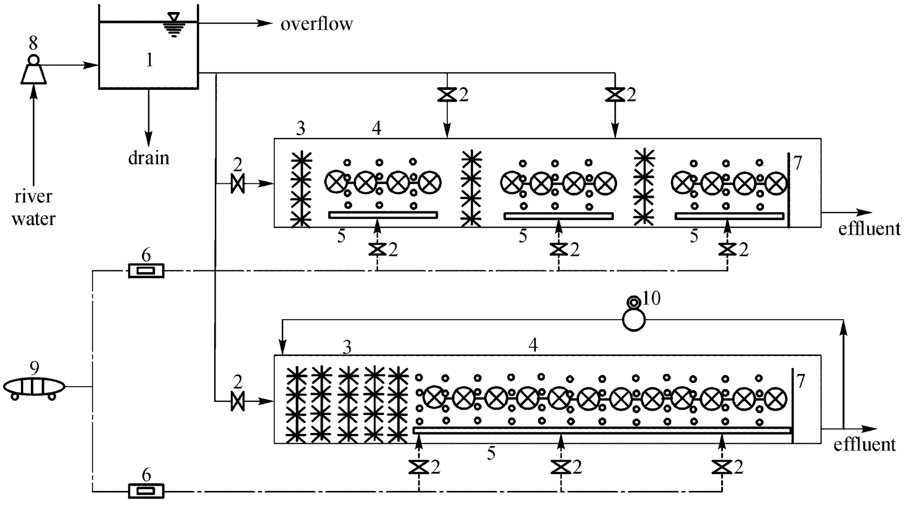
In this study, a field experimental facility was set up near the Daqing River, which is the largest pollutant contributor to the Dianchi Lake. On one hand, only a combined sewer system had been built in the upstream urban catchment of the Daqing River. The treatment capacity of the wastewater treatment plant is very limited, so that the river receives a large amount of domestic wastewater from the urban region. On the other hand, a large number of non-point pollution sources are in the downstream rural region. The Daqing River acts as an extension of the sewer. To consider the removal of nitrogen and phosphorus from the river water, configuration of a step feeding flow [20,21] and an internal recycling [22] were designed to modify the processes into a step-feed biological contact oxidation process (SBCOP) and an inter-recycle biological contact oxidation process (IBCOP). Through long-term operation of the facility, the treatment efficiencies and process parameters of the two units were compared. The feasibility of BCOP in the treatment of polluted river water was also investigated.

2 Methods and materials

2.1 Experimental system

The schematic diagram of the experimental setup is shown in Fig. 1. The experimental facility was placed in the open air. The river water was pumped into a water tank and the water level was controlled by overflow. An SBCOP unit and an IBCOP unit were made of polyvinyl chloride with dimensions of 1.9 m long, 0.3 m wide, and 0.3 m high. The effective volume of each unit was 0.1425 m^3. The influent quantity into the units was controlled by adjusting valves and then the hydraulic retention time (HRT) would be also changed. The SBCOP unit was evenly divided into three segments of the same length, each of which has a feeding pipe of influent at its starting point. In order to optimize the dissolved oxygen (DO) distribution in the SBCOP unit, non-aeration and aeration zones with volume ration of 1:3 in each segments was designed along with the water flow. However, the IBCOP unit has only one feeding pipe of influent at the unit's start, whose non-aeration and aeration zones with volume ratio of 1:3 were also designed along with the water flow. For both SBCOP and IBCOP units, in the non-aeration zones, elastic packing with a diameter of 120 mm, specific surface area of 380 m^2/m^3, and filling density of 77 strings per m^3 were applied as biomass carriers; in the aeration zones, combined packing consisted of plastic rings and fiber, with a diameter of 120 mm, bind distance of 60 mm, and filling density of 1064 sets per m^3 were applied as biomass carriers. All of the effluent from the SBCOP unit was directly discharged after settlement, while part of the effluent from the IBCOP unit was recycled after settlement.

The research was initiated on December 2006, and then went through winter, spring, and summer. This field study



1 water tank; 2 check-valve; 3 elastic packing; 4 combined packing; 5 perforated pipe; 6 gas flowmeter; 7 setting zone; 8 water pump; 9 air pump; 10 peristaltic pump

Fig. 1 Schematic diagram of SBCOP and IBCOP in the field experiment was conducted near the bank of the Daqing River, and the raw water was directly taken from the river. The river quality varied greatly, depending on many factors such as ambient temperature, precipitation, and upstream discharge, etc. The ambient conditions and water quality of raw water are shown in Table 1.

2.2 Experimental methods

According to the weather conditions of Kunming, China, and water quality changes of the Daqing River, the field experiment can be divided into three stages: winter dry season, spring dry season, and summer rainy season.

The facility was initiated in the winter dry season. During this stage, the ratio of inflow at three consecutive distribution points of the SBCOP unit was 4:3:2, and recycling of the effluent was not applied for the IBCOP unit. The total influent of each unit was 26.4 L/h with an HRT of 5.4 h.

When spring dry season arrived, considering the stability of the biological treatment system, the ratio of inflow at three consecutive distribution points of the SBCOP unit was adjusted to 1:1:1, and a recycling ratio of 200% was applied for the IBCOP unit. Considering the lower substrate concentration of the raw water and positive effect of temperature rise on biological treatment, the total influent of each unit was 71.3 L/h with an HRT of 2 h.

During the summer rainy season, in order to enhance the nitrification in the two biological treatment units, the total influent of each unit was recovered to 26.4 L/h with an HRT of 5.4 h, while maintaining the ratio of 1:1:1 for the inflows at three consecutive distribution points of the SBCOP and the recycling ratio of 200% for the IBCOP.

2.3 Analytical methods

The chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), nitrate nitrogen ($NO_3^- - N$), and ammonia nitrogen (NH_3–N) in waters were determined according to standard methods, i.e., Dichromate Method, Alkaline Potassium Persulfate Digestion-UV Spectrophotometric Method, Ammonium Molybdate Spectrophotometric Method, UV-Spectrophotometry Method, and Nesster's Reagent Colorimetric Method, respectively. Chlorophyll-a was determined using Spectrophotometric Method. The main instruments used in this study were a spectrophotometer (721, Shanghai Jinghua Scientific Instrument Co., Ltd, China) and a UV spectrophotometer (UV752, Shanghai Precision & Scientific Instrument Co., Ltd, China). Water temperature, DO concentration, and pH were measured using selective electrodes, DO meter (SevenGo pro SG6, METTLER TOLEDO, Switzerland), and pH meter (SevenGo SG2, METTLER TOLEDO, Switzerland), respectively.

3 Results and discussion

3.1 Variation of water temperature, DO, and pH

The water temperatures of influent and effluent in the two biological units are shown in Fig. 2. The water temperatures were below 15°C during the winter season and greatly increased during the spring and summer seasons with a large variation due to the climate changes. There was no marked difference between the influent and effluent.

The DO concentrations of influent and effluent in the two biological units are shown in Fig. 3. There was a large

Table 1 Local climate and river water conditions during the experiment periods

	winter dry season (2006/12/19–2007/01/31)	spring dry season (2007/03/03–2007/05/08)	summer rainy season (2007/05/13–2007/06/14)
air temperature/°C	0–17	6–28	10–28
rain	less precipitation (only one snowfall)	less precipitation	frequent rain with heavy precipitation
sunshine	strong sunshine	strong sunshine	most rainy and cloudy days, except for a few strong sunshine days
source of wastewater	Upriver gate-valve was opened, so that domestic sewage flowed into the river channel.	Upriver gate-valve was closed, so that lake water flowed back into the river channel from the Dianchi lake.	Upriver gate-valve was opened in the rainy days, so that the mixture of rainwater and sewage flowed into the river channel; otherwise the gate-valve was closed, so that lake water flowed back into the river channel.
water temperature/°C	8.5–14.8	13.9–24.2	17.9–32.6
DO/($mg \cdot L^{-1}$)	0.0	0.7–9.8	0.1–7.6
COD_{Cr}/($mg \cdot L^{-1}$)	114.7–301.5	48.3–201.2	48.8–174.7
TN/($mg \cdot L^{-1}$)	26.31–37.89	7.83–19.93	9.45–18.55
TP/($mg \cdot L^{-1}$)	0.29–1.74	0.13–0.57	0.36–2.24

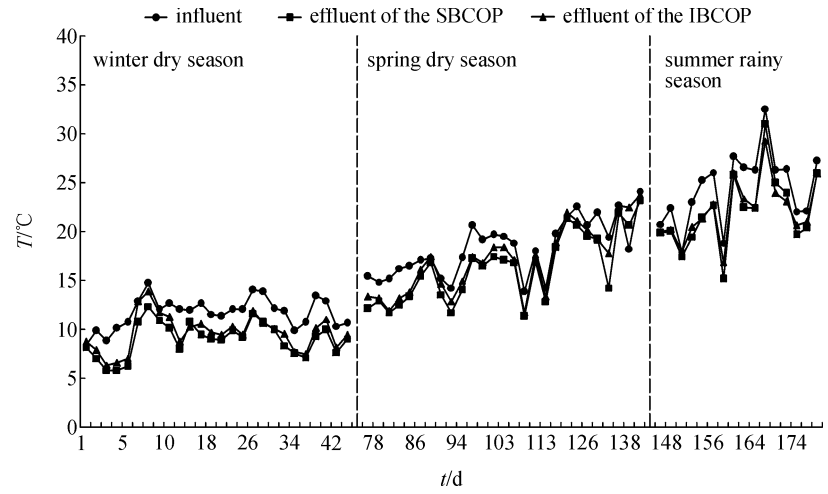


Fig. 2 Variation of water temperature during the experimental period

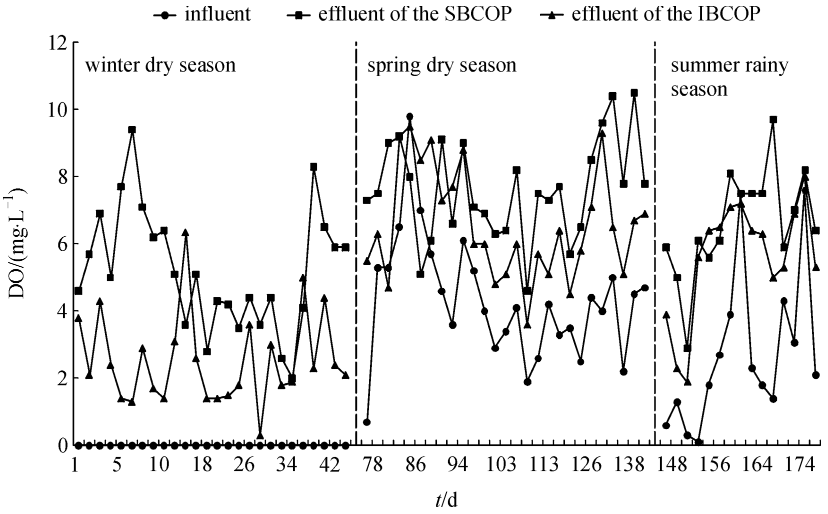


Fig. 3 Variation of DO during the experimental period

variation of DO concentrations in influent and effluent during the whole research period. The DO concentrations in influent during the spring and summer were higher than that during the winter, because of the growth of algae and the use of aeration equipment in the river. The DO concentrations in the effluent of the SBCOP were much higher than that of the IBCOP, with the average difference of 2.7 mg/L, 1.1 mg/L, and 0.9 mg/L during the winter, spring, and summer seasons, respectively.

The pH values of influent and effluent in the two biological units are shown in Fig. 4. During the whole research period, the average pH value of the influent was 7.7, and the average pH value of the SBCOP effluent and the IBCOP effluent were 8.3 and 8.1, respectively. There was a significant difference of pH values between influent and effluent of the biological treatment units during the winter period. During the spring period, the pH values of influent and effluent of the biological treatment units fluctuated greatly; however, their difference became weak. During the summer period, the pH values of influent and effluent of the biological treatment units showed a general trend of decline.

3.2 Removal of COD, TN, and TP during the winter dry season

During the winter dry season, the quality of raw water was relatively stable and the average COD, TN, and TP were 166.7 mg/L, 34.9 mg/L, and 1.11 mg/L, respectively. The COD, TN, and TP removal efficiencies by the two biological treatment units during the winter dry season are shown in the left parts of Figs. 5, 6, and 7, respectively.

The average COD removal efficiencies of the SBCOP unit and the IBCOP unit were 58.0% and 53.4%, respectively. The TP removal efficiencies of the two biological treatment units fluctuated greatly, with an

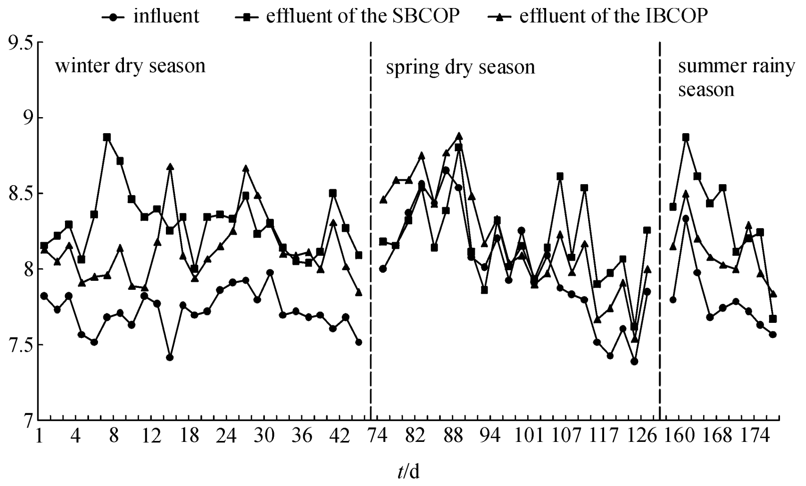


Fig. 4 Variation of pH during the experimental period

average of 40.4% and 26.6% for the SBCOP unit and the IBCOP unit, respectively. However, the TN removal efficiencies were very low, possibly due to the low temperature inhibition on nitrification and denitrification, with an average of 9.7% and 4.0% for the SBCOP unit and the IBCOP unit, respectively. Moreover, by comparison, the removal efficiency of pollutants by the SBCOP unit experienced a stronger fluctuation, although on the average it slightly outweighed that by the IBCOP unit.

The microscopic observation on the biofilms of the two units showed that the microbial diversities were limited, and the biomass concentration was very low. This might be the reason for the fluctuation in treatment efficiency during the first stage.

3.3 Removal of COD, TN, and TP during the spring dry season

During the spring dry season, the average COD, TN, and TP were 83.1 mg/L, 13.0 mg/L, and 0.37 mg/L, respectively. Under the condition of this water quality, the ratio of inflows of the SBCOP unit was adjusted to 1:1:1, and the IBCOP unit was operated with a recycling ratio of 200%.

After two weeks' operation with an HRT of 5.4 h, the biofilm growth appeared to be abnormal because of easy sloughing and thinner layer. Meanwhile, the algal biomass increased greatly under radiation of strong sunlight, and the level of chlorophyll-a in the liquid reached 13.4 mg/L. When the HRT was reduced to 2 h, the biofilm growth recovered at a normal state. The microscopic results indicated a larger diversity of biophase with many kinds of algae and indicator microorganisms, which may lead to a more profound occurrence of a symbiotic algae-bacteria system. The COD, TN, and TP removal efficiencies by the two biological treatment units during the spring dry season are shown in the middle parts of Figs. 5, 6, and 7, respectively.

Because of the low influent organic load during the spring, under the condition of 5.4 h HRT, the average COD removal efficiencies of the SBCOP unit and the IBCOP unit were 58.0% and 34.4%, respectively. However, under the condition of 2 h HRT, the COD removal efficiency was increased, and the average COD removal efficiencies of the SBCOP unit and the IBCOP unit were 46.4% and 41.5%, respectively. Because of temperature increase, the TN removal efficiencies rose to 24.7% for the SBCOP unit and 18.7% for the IBCOP unit. Moreover, the TP removal efficiencies were also increased with a large fluctuation, and the average removal efficiencies were 45.1% for the SBCOP unit and 52.2% for the IBCOP unit. Comparing the removal efficiencies of three major pollutants by the SBCOP and the IBCOP unit under the condition of different HRT, it can be concluded that the SBCOP unit had a better adaptability to hydraulic load than the IBCOP unit did, although the latter performed better in the reduction of the pollutants.

Although the water temperature increased during this stage, the water quality still changed acutely. Moreover, the sewage interception project of the Daqing River was put into action, and an upriver gate-valve was closed to hold up and induce the polluted river water into a diversion tunnel. Therefore, the lake water flowed back into the original river channel from the Dianchi Lake. All these influenced the treatment efficiencies and microbial activities. However, by adjusting HRT, the effluent quality improved slightly.

3.4 Removal of COD, TN, and TP during the summer rainy season

During the summer rainy season, the influent of the system was a mixture of agricultural drainage, sewage in storm runoff, and lake water intruded from the Dianchi Lake. The two units were operated under an HRT of 5.4 h due to large fluctuation of water quality. The COD, TN, and TP removal efficiencies by the two biological treatment units are shown in the right parts of Figs. 5, 6, and 7, respectively.

The COD removal efficiencies fluctuated greatly, with 25.0%–73.3% (average 66.5%) in the SBCOP unit and 7.4%–74.7% (average 59.8%) in the IBCOP unit. The average TN removal efficiencies of the SBCOP unit and the IBCOP unit were 27.2% and 32.9%, respectively. The TP removal efficiency was also greatly affected by the influent quality, which were 20.4%–88.8% (average 47.3%) and 34.8%–96.9% (average 55.8%) for the SBCOP unit and IBCOP unit, respectively. Therefore, the two units had similar performance in the reduction of three major pollutants and strong adaptability to hydraulic loading.

With the arrival of summer, the duration and strength of sunlight increased. The accumulation of duckweeds entering the biological treatment units with raw water covered the water surface of the non-aeration region. In the aeration region, the large hydrophytes twisted with filling media and gradually filled the whole biological treatment units, which could also act as additional media for biomass growth and thus enhancing the adaptability to hydraulic loading. The water turned to green resulting from a large amount of algae in the raw water entering the units with 35.6 mg/L of chlorophyll-a. The microscopic results indicated a more abundant diversity of biophase in each unit.

The comprehensive comparison of pollutant removal efficiencies by the two units is shown in Table 2.

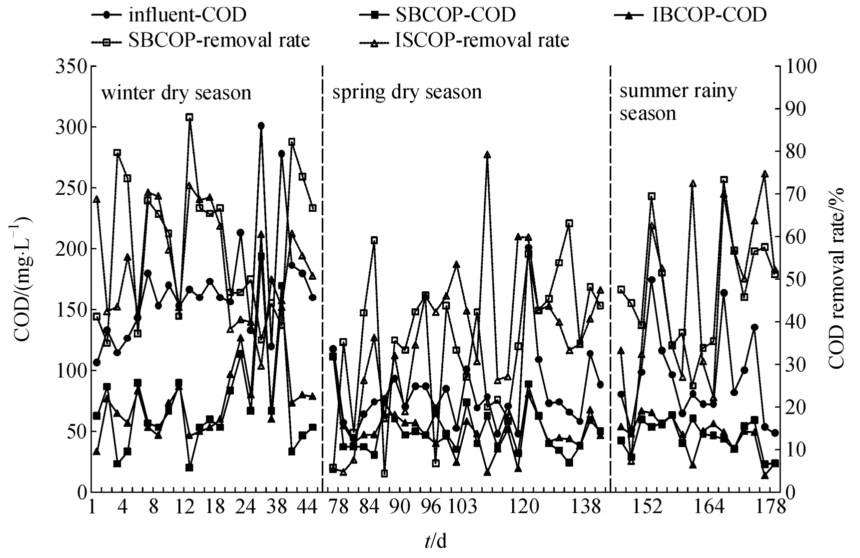


Fig. 5 Variation of COD and the removal efficiencies during the experiment period

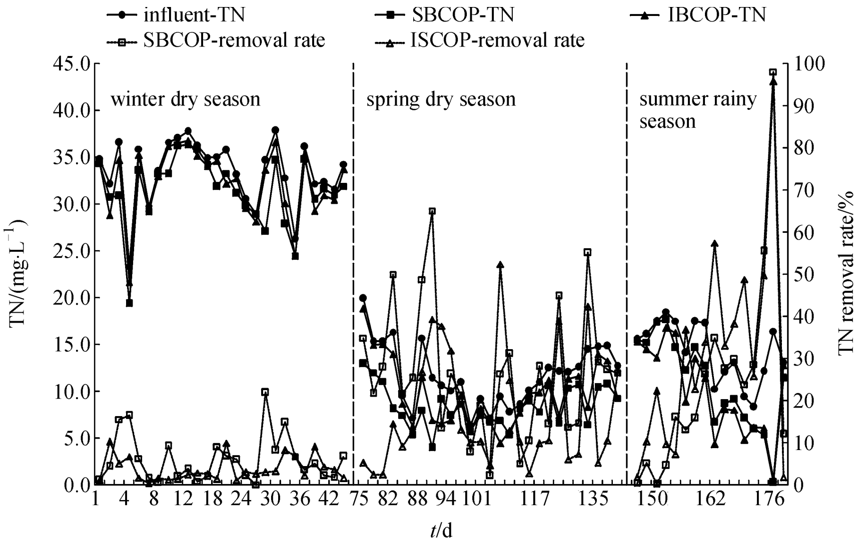


Fig. 6 Variation of TN and the removal efficiencies during the experiment period

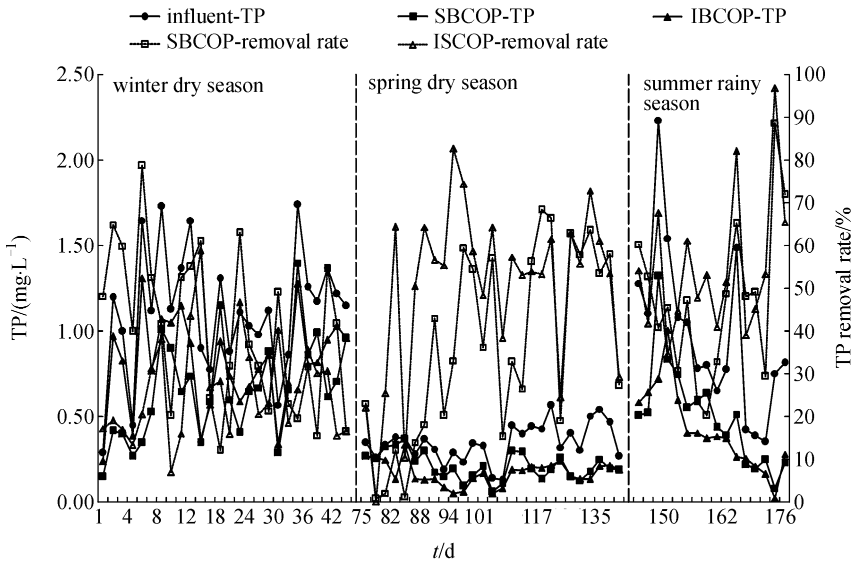


Fig. 7 Variation of TP and the removal efficiencies during the experiment period

Table 2 Comparison of the treatment efficiencies of SBCOP and IBCOP at different stages

pollutant		winter dry season (2006/12/19–2007/01/31)		spring dry season (2007/03/03–2007/05/08)		summer rainy season (2007/05/13–2007/06/14)	
		SBCOP	IBCOP	SBCOP	IBCOP	SBCOP	IBCOP
COD_{Cr}	influent/(mg·L^{-1})	114.7–301.5	114.7–301.5	48.3–201.2	48.3–201.2	48.8–174.7	48.8–174.7
	effluent/(mg·L^{-1})	20.0–205.8	33.3–211.9	20.7–88.7	19.3–80.7	13.6–77.3	11.9–92.0
	removal efficiency/%	28.1–82.2	29.6–72.0	23.5–71.9	7.7–66.1	21.6–77.6	6.8–77.8
TN	influent/(mg·L^{-1})	26.3–37.9	26.3–37.9	7.8–19.9	7.8–19.9	9.5–18.6	9.5–18.6
	effluent/(mg·L^{-1})	23.2–36.5	24.2–37.6	5.4–18.4	4.3–18.9	3.9–17.7	4.4–18.0
	removal efficiency/%	0.2–15.7	0.4–17.9	2.9–35.0	0.0–52.5	0.2–67.9	1.8–57.5
TP	influent/(mg·L^{-1})	0.29–1.74	0.29–1.74	0.13–0.57	0.13–0.57	0.36–2.24	0.36–2.24
	effluent/(mg·L^{-1})	0.15–1.4	0.24–1.63	0.05–0.3	0.04–0.34	0.08–1.86	0.02–1.65
	removal efficiency/%	16.5–78.8	3.4–60.6	15.4–71.7	10.4–82.8	16.7–88.8	26.4–96.9

3.5 Nitrogen transformation

During the experiment period, we also put emphasis on nitrogen transformation in the SBCOP and the IBCOP units by monitoring the influent and effluent NH_3-N and NO_3^- −N, and the results are shown in Figs. 8 and 9, respectively.

The nitrification was greatly affected by temperature. During the winter, the water temperature was usually below 15°C and the amount of produced nitrate was insignificant. The nitrogen loss was also very low, and the average removal efficiencies by the SBCOP unit and the IBCOP unit were 9.7% and 4.0% (Fig. 6 and Table 2), respectively. With the temperature increasing, the nitrification rate increased during the spring and summer seasons. Moreover, the rise of DO concentration in raw water (0.1–9.8 mg/L) favored the nitrification (Fig. 9). The NH_3–N removal efficiencies averaged 66.2% for the SBCOP and 25.5% for the IBCOP in spring, and 66.4% for the SBCOP and 46.7% for the IBCOP in summer (Fig. 8). The average TN removal efficiencies by the SBCOP unit and the IBCOP unit were 24.7% and 18.7% in the spring, and 27.2% and 32.9% in the summer, respectively (Fig. 6 and Table 2). It is supposed that the denitrification rate was deteriorated since the DO level was high [14]. However, partial denitrification may also happen even at high ambient DO level because of oxygen diffusion limitation in the biofilm. The temperature rise also enhanced denitrification, which made higher nitrogen removal efficiencies during the spring and summer than that during the winter (Fig. 6).

Because of the application of step feeding and staged aeration, the SBCOP unit had a high adaptability to water quality fluctuation. The SBCOP unit performed better in

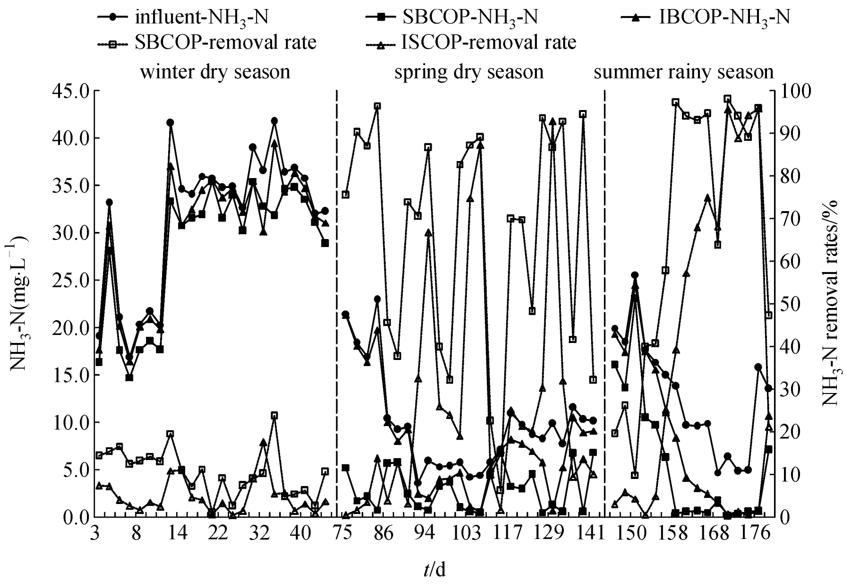


Fig. 8 Variation of NH_3–N and the removal efficiencies during the experiment period

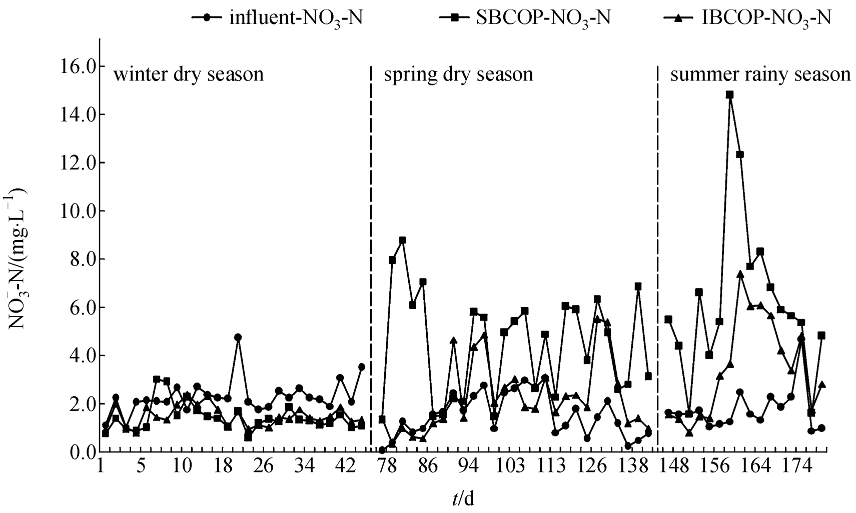


Fig. 9 Variation of NO_3^- –N during the experiment period

ammonia removal, nitrate production, and TN removal than the IBCOP unit did, although there was no marked difference in nitrogen transformation during the winter. During the winter and spring, earlier appearance of a large amount of duckweeds and other large hydrophytes grew in the SBCOP unit, providing a nice ambient condition in addition to serving as biomass growth media, which may also contribute to the improvement of pollutant removal efficiency. Additionally, duckweeds growth, which could effectively prevent ray radiation at non-aeration zones, could enhance denitrification and nitrogen utilization. Such phenomena became remarkable in the summer, when each of the units maintained stable nitrogen removal efficiency although the influent water quality fluctuated greatly. However, the TN removal efficiency by the SBCOP unit was lower than that of the IBCOP unit because the SBCOP unit could effectively improve the level of effluent DO but inhibited the denitrification (Fig. 3).

Compared with other similar studies, this field experiment provides practical value for polluted river water treatment. Wang et al. [13] used a suspended filler moving-bed to treat the branch water of the Suzhou River, China, in one winter season. Under a water temperature of 8–12°C and HRT of 1 h, the effluent COD_{Cr} averaged 34.7 mg/L, and the removal efficiencies of NH_3–N was lower than 30% since nitrification was inhibited by lower water temperature; Wang et al. [14]operateda suspended carrier biofilm reactor for 25 days and observed the removal of

COD_{Cr} and NH_3–N from the polluted river water in Tsinghua University campus, China. Under a water temperature of 15–20°C and HRT of 1 h, the reactor reached an average COD_{Cr} and NH_3–N removal efficiency of 56.9% and 76.0%, respectively. Park et al. [15] designed a fixed-bed biofilm reactor to treat polluted stream water in a year. With the help of a sludge discharger and backwashing system, the annual mean removal efficiencies of BOD and TSS were 87.3% and 86.8%, respectively under large fluctuation of water temperature and DO. Xiao et al. [19] applied a biocontact oxidation process with an elastic packing and micropore aerator to remove NH_4^+-N in the polluted raw water of water sources. The treatment efficiencies varied from 64.0%–95.0% in the summer to 40.0%–63.0% in the winter under similar water sources and running parameters. In our study, the treatment efficiencies of the SBCOP and the IBCOP for COD_{Cr}, TP, TN, and NH_3–N fluctuated with the local weather conditions and river water qualities of the influent. The SBCOP had higher adaptability and better performance than the IBCOP did for the long-term water quality improvement of polluted river.

4 Conclusions

The treatment performance of an SBCOP unit and an IBCOP unit applied for heavily polluted river water were investigated in this research. The main results are summarized as follows:

(1) The SBCOP and the IBCOP can be adaptable to the fluctuation of climate and water quality through the optimization of HRT, aeration strength, and ratio of inflow at consecutive distribution points or recycling ratio. The high organic loading favored high COD removal efficiency. TN removal efficiency was subject to water temperature and DO level. TP could be effectively cut down during each season; however, fluctuation of removal efficiency could be observed due to the variation of microorganisms. The SBCOP unit had higher adaptability and better performance in the reduction of pollutants, i.e., with the average removal efficiency for COD, TN, and TP of 58.0%, 9.7%, and 40.4% in the winter, 46.4%, 24.7%, and 45.1% in the spring, and 66.5%, 27.2%, and 47.3% in the summer, respectively. Therefore, SBCOP is more applicable for the treatment of river water entering the Dianchi Lake.

(2) Nitrification rate was greatly affected by influent temperature, and denitrification rate was greatly affected by DO level. The nitrification was poor during winter, while it increased with the rise of temperature and DO level during spring. Meanwhile, the denitrification was also increased. During the summer, the optimization of operational conditions, the contribution of duckweeds, and other hydrophytes also improved the nitrogen removal efficiency. During each season, the nitrification in the SBCOP unit was higher than that in the IBCOP unit. The TN removal efficiency in the SBCOP unit was higher than that in the IBCOP unit during the winter and spring seasons. However, during the summer season, the TN removal efficiency in the SBCOP unit was poorer than that in the IBCOP unit, possibly due to the inhibition of denitrification by higher DO level in the SBCOP unit.

(3) The symbiotic algae-bacteria system could be conducive to the removal of pollutants. The duckweeds in non-aeration zones could also favor the removal of pollutants.

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