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A novel bamboo fiber biofilm carrier and its utilization in the upgrade of wastewater treatment plant

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ABSTRACT

A novel biofilm carrier (BFBC) was prepared with bamboo fiber as raw material and its characteristics, including specific surface area, hydrophilicity, and adsorption capacity were investigated. The comparison with conventional combined carrier for the removal of organics, N, and P using bio-contact oxidation reactor (BCOR) was carried out. The application of BCOR filled with BFBC in upgrading the existing activated sludge system of wastewater treatment plant was further studied. The specific surface area of BFBC was 5393 m^2/m^3, thoroughly saturated with water in 30 min. The BCOR filled with BFBC started up more rapidly than BCOR filled with combined carrier, and the removal efficiencies for chemical oxygen demand (COD), N, and P were significantly higher in BCOR filled with BFBC than combined carrier during start-up period. Moreover, the BCOR filled with BFBC showed higher resistance to pollutants load impact. Compared with the existing activated sludge system, the BCOR was more efficient in pollutant removal and resistance to load fluctuation, and the effluent COD, ammonium nitrogen (NH_4^+-N), and total nitrogen meet the class IA standard of municipal wastewater treatment plant.

Keywords: Bamboo fiber; Biofilm carrier; Fixed-biofilm reactor; Removal efficiency

1. Introduction

Most municipal sewage treatment plants in China are confronted with upgrade as the application of new discharge standard of pollutants for municipal wastewater treatment plant. The chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), and total phosphorus (TP) would be reduced by 16.7, 25, 37.5, and 50% according to the new discharge standard. How to retrofit the existing facility with minimum changes and meet the new wastewater systems effluent regulations with substantially less cost than traditional plant expansion have attracted considerable attention in recent years. Biofilm process is an attractive option because of high removal efficiency, cost effective, low-footprint alternative, and low sludge yield [1,2]. The carrier for retain micro-organisms is the core part of biofilm process, which would affect the performance of biofilm process significantly [3]. The ideal biofilm carrier should be biocompatible, biodegradable with high surface area for micro-organism immobilization, and good mechanical strength [4,5]. Besides, the carrier with good hydrophilicity would

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favor cell adhesion and facilitate cell proliferation, and therefore, reduce the start-up time of the treatment system [6]. At present, carriers made of polyvinyl chloride [7], polypropylene [8], polystyrene [9], and polyester fiber [10] are widely used in the biofilm process. However, these raw materials are derived from the nonrenewable oil resources, and would not be easily degraded once wasted, causing second pollution. Therefore, a considerable amount of research has focused on the preparation of biofilm carrier with relatively abundant, easily available, and degradable materials [11,12].

Bamboo, an abundant natural resource in Asia and Middle and South America, has been traditionally used to construct various living facilities and tools due to its rapid growth rate and universality [13,14]. Bamboo fiber extracted from bamboo is a kind of natural fiber material, used for construction purposes as well as for the pulp and paper industry [15]. Compared with traditional synthetic fiber, bamboo fiber is gaining popularity because of low price, durability, sustainability, and biodegradability [16]. It is composed of cellulose and lignin as other plant fiber, with high specific surface area, hydrophilicity, and luxurious inter-connected pores, which allows the formation of attached-growth biomass [17]. In previous literatures, bamboo and its derivatives, including bamboo pieces, spheres, and filamentous bamboo, have been used as the main materials of biofilm carrier in biological treatment processes [18–20].

The present work was undertaken to prepare biofilm carrier (BFBC) with bamboo fiber as raw materials, and compared the performance of bio-contact oxidation reactor (BCOR) filled with BFBC and conventional combined carrier separately for the removal of organics, N, and P. The potential application of BCOR filled with BFBC in upgrading existing wastewater treatment plants was further investigated.

2. Materials and methods

2.1. Preparation of bamboo fiber biofilm carrier (BFBC)

Bamboo fiber, purchased from Changshu, was mixed with polyester fiber at a ratio of 30, 50, and 70% (v/v), separately. The mixtures were then paved to a thin layer with the thickness of 2–3 mm. A piece of foam plastic (2–5 mm) was laid in the middle of two above mixture layers. The resultant composite material was finally bonded by needle punch. The thickness of the resultant BFBC was around 6–12 mm, and the length and width could be tailored as needed.

2.2. Characterization of BFBC

The specific surface area of BFBC was measured by accelerated surface area and porosimetry system (USA, Micromeritics ASAP 2020) using N_2 gas as adsorbate at 77.37 K. A Hitachi S4700 series scanning electron microscope (SEM) was used to observe the surface physical morphology of BFBC. Surface hydrophobicity of BFBC was characterized by gravimetric method. A piece of BFBC (5 cm × 3 cm), pre-dried to a constant weight was put into the beaker with 800 mL deionized water without any force. Record the weight at the end of pre-determined time intervals and repeat. The assays were performed in six replicates. The adsorption capacity of BFBC was investigated using a batch mode operation. The experiments were conducted in 250 mL conical flasks with 100 mL synthetic wastewater (pH 6.98, NH_4^+-N 19.19 mg/L, TP 5.73 mg/L) in a thermostated shaker at a speed of 150 rpm under 293 K. Samples were withdrawn from the flasks at pre-determined time and analyzed for NH_4^+-N and TP.

2.3. Comparison with combined carrier

The comparison with combined carrier was carried out in two BCORs (15 cm × 15 cm × 60 cm) fabricated from PVC sheets (8 mm thickness) with effective volume of 11.25 L. BCOR1 was filled with 10 pieces of combined carrier, which was 180 mm in diameter and installed every 80 mm in the reactor. BCOR2 was filled with 0.36 m^2 BFBC having the same packing density. In both, the height of the carrier was 40 cm. The BCOR was aerated by air pump at the bottom of the reactor to meet the desired DO concentration of 2 mg/L. Synthetic wastewater (COD 120–250 mg/L, NH_4^+-N 13–38 mg/L, TN 17–45 mg/L, TP 2–3 mg/L, pH 6.5–7.5) was fed constantly from the storage tank throughout peristaltic pump to the bottom of BCOR. In the first 11 days, the BCOR was started by feeding with wastewater at flow rate of 1.5–1.8 L/h, so that the biofilm could form on the carrier gradually. After obtaining stabilized performance, the system was operated at a flow rate of 2.25 L/h, that was, hydraulic retention time (HRT) 6 h.

2.4. Potential application in the upgrade of wastewater treatment plant

The trail was conducted in the Hengfan wastewater treatment plant in Lin'an city, Zhejiang Province, China (Fig. 1). Wastewater was fed from the anaerobic oxidation tank of the wastewater treatment plant and into the BCOR (2 m × 0.5 m × 1.1 m) fabricated from

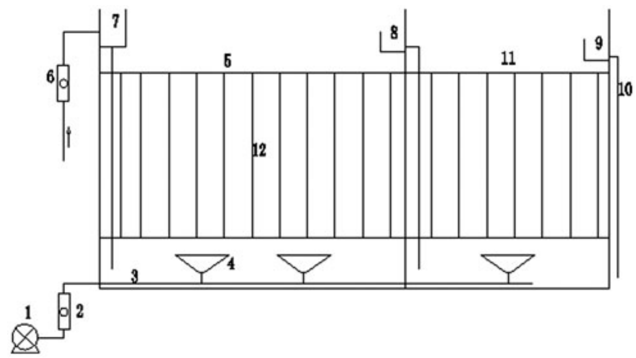

Fig. 1. Flow chart of the BCOR system (1) fan (2) air flowmeter (3) air pipeline (4) micropore diffuser (5) first contact oxidation tank (6) flowmeter (7) inflow tank (8) first effluent tank (9) second effluent tank (10) effluent pipeline (11) second contact oxidation tank (12) bamboo fiber biofilm carrier.

PVC sheet with effective volume of 0.9 m^3. The BCOR was divided into two compartments according to the volume ratio of 3:2. Micropore aerators were installed at the bottom to ensure that the air equally distributed among the reactor, and the gas to liquid ratio was 18:1. There were two sludge pipes at the bottom. The BFBC was cut into strips (65 cm × 2 cm), and tied to plastic rope every 3 cm intervals. Both ends of the rope were tied to the supporters in the reactor. The line of the BFBC was installed every 10 cm. Total BFBC amount was 210, with the packing area of 2.73 m^2. The performance of BCOR for removal of COD was compared with the existing activated sludge system of wastewater treatment plant. The experiment was conducted from September to December, and the temperature range was 13–29˚C.

2.5. Analytical methods

The method employed for determining COD, NH_4^+-N, TN, and TP followed the Standard Methods [21]. DO and pH were analyzed using portable DO meter (JPB-607, Leici, China) and digital pH meter (FG2-ELK, Mettler Toledo, USA). The thicknesses of biofilms on the BFBC and combined carrier were examined using a vernier caliper at three depths of 100, 200, and 300 mm from the bottom of the carrier.

3. Results and discussion

3.1. Characterization of BFBC

The weight of the BFBC increased with immersion time in water and reached saturation in about 30 min. The water holded was calculated to be 6.9 g/g, 7.6 g/g, and 8.0 g/g for BFBC-30, BFBC-50, and BFBC-70, separately, indicating the increase of bamboo fiber enhanced the wettability of BFBC. This might be attributed to the differences of chemical structure and constitutes of bamboo fiber and polyester fiber. The surface of bamboo fiber was coarse with numerous fine grooves, and the cross-section is longitudinal covered with large and small gaps and microholes, which can absorb moisture in an instant as the capillary. Furthermore, it is composed of cellulose, which is derived from D-glucose units. Each of the glucose-based rings has three hydroxyl groups which lie on the 2,3, and 6 carbon atoms, respectively. These hydroxyl functional groups contribute strong polarity and high water absorption to the bamboo fiber [22]. Wherein, the polyester fiber is prepared by copolymerizing polyethylene acid and ethylene glycol. The hydrophilicity is relative poor due to its symmetrical molecular structure, high crystallinity, and the absence of high polar groups on the surface [23,24]. As the ratio of bamboo fiber was more than 70%, bamboo fiber was observed to be lodged, adhering to the EVA layer, as a result affecting the formation of biofilm.

The adsorption capacity of BFBC for NH_4^+-N increased with time and leveled off with the maximum of 464.27, 394.57, and 362.62 mg/kg for BFBC-70, BFBC-50, and BFBC-30, respectively (Fig. 2). The adsorption capacity of BFBC with more bamboo fiber is significantly higher than two other BFBCs. This result is presumably to the grooves, gaps, and holes structure of the bamboo fiber, and special groups of the cellulose. Many previous literatures have reported the adsorption of cellulosic materials, such as leaf powder [25], beech, and birch wood [26].The adsorption capacity for phosphorus showed the same trend, however, it is much lower than that of NH_4^+-N. It might be attributed to the steric hindrance effects of phosphate groups [27]. Thus, BFBC-70 was selected for the reactor study.

The SEM of a piece of BFBC (5 cm × 3 cm × 2 mm) weighted 0.3816 g demonstrated there were 17,100 bamboo fiber. The BET surface area was 8.48 m^2/g. If the reactor was filled with 2.5 m^2 BFBC/m^3, the specific surface area of BFBC was 5,393 m^2/m^3, which was significantly higher than carriers made from polypropylene, polystyrene, and polyester fiber (Table 1).

3.2. Comparison with conventional combined carrier

3.2.1. COD removal

The BCOR was inoculated with activated sludge from the Hengfan wastewater treatment plant. A total

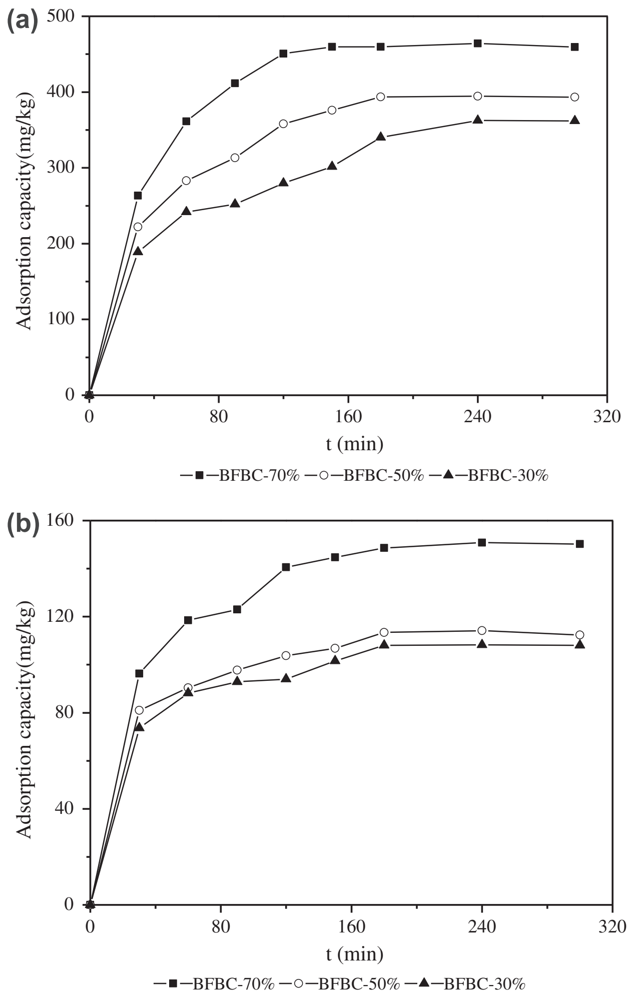

Fig. 2. Adsorption capacities of bamboo fiber biofilm carrier (BFBC) for NH_4^+-N (a)and TP (b) (initial NH_4^+-N: 19.19 mg/L; initial TP: 5.73 mg/L; temperature: 293 K; BFBC dosage: 5 cm × 3 cm).

volume of 600 mL of activated sludge was added to the reactor. Then the whole reactor was submerged into feed water, aerated, and sludge circulated to achieve complete mixing and ensure a good contact between the micro-organisms and the carrier. After a batch inoculation period of 24 h, a continuous inlet flow of synthetic wastewater was applied to maintain a constant rate of 1.5 L/h. Seventy-two hours later, the rate increased to 1.8 L/h.

After 1 d of continuously fed with synthetic wastewater, several yellow spots were observed on the surface of BFBC. Three days later, almost all BFBC were covered by biofilm, wherein some fibers of combined carrier adhered with each other and some yellow pots were found on the surface. At the sixth day, the COD removal efficiencies of BCOR1 and 2 reached 70.96 and 74.93%, separately. In the following five days, as the influent COD varied in the range of 158–223 mg/L, both COD removal efficiencies of BCOR1 and 2 were above 65%, indicating the biofilm formation was achieved. The thickness of the biofilm on the surface of BFBC was 3–5 mm, and that of the combined carrier was 2–3 mm. The microscopic examination indicated there were several protozoa present in the biofilm. The carriers before and after biofilm formation were shown in Fig. 3.

The COD removal efficiency of BCOR2 was significantly higher than BCOR1 during the start-up period as shown in Fig. 4(a). It might be attributed to the special properties of bamboo fiber. Biofilm formation was correlated with surface roughness, specific surface area, and hydrophilicity of carrier [34]. Rough surface could enhance the adherence of organic pollutants, the effective contaction area between micro-organisms and carriers, and therefore, facilitate cell proliferation and biofilm formation and meanwhile reduce the shearing impact of hydraulic power, preventing the biofilm fall off [35]. Biomass was much higher on the surface of carriers with larger specific surface area as more sites provided. The friction coefficient of bamboo fiber was huge with many meshy inter-connected pores inside,

Table 1
Specific surface area of biofilm carriers

Types of carriers	Specific surface area/(m^2/m^3)	References
Porous polyacrylonitrile balls	237	[28]
Polypropylene carrier	350	[29]
Kaldnes K3 carrier (Polyethylene)	500	[30]
Polyurethane	900	[31]
Tube chips of biocarrier (mixture of polyethylene and inorganic particles)	800	[32]
JDRZ soft combined carrier	1,250	
Fiber threads carrier	2,800	[33]
Soft carrier	1,390–9,891	
BFBC	5,393	–

Fig. 3. Photos of BFBC (left) and combined carrier (right) before and after the biofilm formation.

enhancing the micro-organism growth and proliferation in the pores. The previous studies demonstrated the hydrophobic carrier was adaptable for micro-organism adherence and spreading of cells. The carrier modified in the hydrophilic could start up faster, and the biofilm was difficult to fall off with the shearing impact of hydraulic power and tolerant to the load fluctuation [36]. At the steady state, COD removal efficiency of BCOR2 was slightly higher than that of BCOR1. However, the BCOR2 showed better tolerance to COD load fluctuations. As the influent COD varied from 127.6 to 204.8 mg/L, COD removal efficiency of BCOR2 was more than 50%, while the minimum value of BCOR1 was 37.3%.

3.2.2. Nitrogen removal

Both the reactor showed good performance for nitrogen removal (Fig. 4(b)). As the influent NH_4^+-N varied from 12.67 to 34.84 mg/L, NH_4^+-N removal efficiencies of BCOR1 and 2 were 69.3% and 74.2% (average value), separately. A sharp decrease of NH_4^+-N removal was observed on the 19th day, which was attributed to the instability created by the sudden increase of influent NH_4^+-N load. However, both the reactors were recovered rapidly to a steady state (2 d), indicating the biomass acclimatization to higher load as the fraction of active biomass in the reactor increased. In the beginning of the process, the NH_4^+-N removal efficiency of BCOR2 was obviously greater than BCOR1, which may due to the adsorption capacity of BFBC. The ammonium in the BCOR system was removed from the solutions via the adsorption on the BFBC and consequently degradation by the biofilm on the BFBC. The adsorption capacity of BFBC to ammonium would accelerate the removal of ammonium. The adsorption trial suggested that the BFBC had potential adsorption ability for NH_4^+-N.

As for TN removal, the removal efficiency of BCOR2 is significantly higher than BCOR1 as time progressed (Fig. 4(c)). This was presumably due to the simultaneous nitrification–denitrification (SND) in attached-growth biofilm. In the system, DO and substrate concentration grads resulted in different micro-environments in attached-growth biofilm which might make SND takes place. SND is relevant to the amount and activity of anaerobic micro-organisms, which is indirectly controlled by the thickness of anaerobic layers in attached-growth biofilm [37]. When the biofilm reached certain thickness, it would lead to the formation of aerobic, anoxic, and anaerobic zone, which provided essential conditions for SND. The BFBC can maintain high-biomass concentration, encouraging the culture of slow-growing nitrifying and denitrifying bacteria. Moreover, less surplus sludge was produced during the operational period, which thus resulted in prolonged sludge age of the whole system. The microbial morphology examination suggested the inner biofilm on the BFBC was dark brown, indicating the formation of anaerobic zone in the biofilm.

3.2.3. TP removal

The TP removal efficiencies of BCOR1 and BCOR2 during the experiment are shown in Fig. 4(d). TP removal in the BCOR1 and BCOR2 was 27.5 and 28.1%, separately, with the maximum of 39.5 and 40.5%. The results showed that both the reactors may be not available for P removal. In conventional biological phosphorus removal system, polyphosphate-accumulating organisms (PAOs) take-up volatile fatty acids and store them internally to form polyhydroxyalkanoates (PHAs). The energy required for this process is derived from the hydrolysis of intracellular polyphosphate, as a result, release phosphorus. In the presence of oxygen, PAOs utilize the stored PHAs as an energy source to take-up P from the solution to regenerate the polyphosphate used in the anaerobic reactor. In this process, the PAOs take-up more P than that released during the anaerobic stage, therefore, P in wastewater could be effectively removed with rich

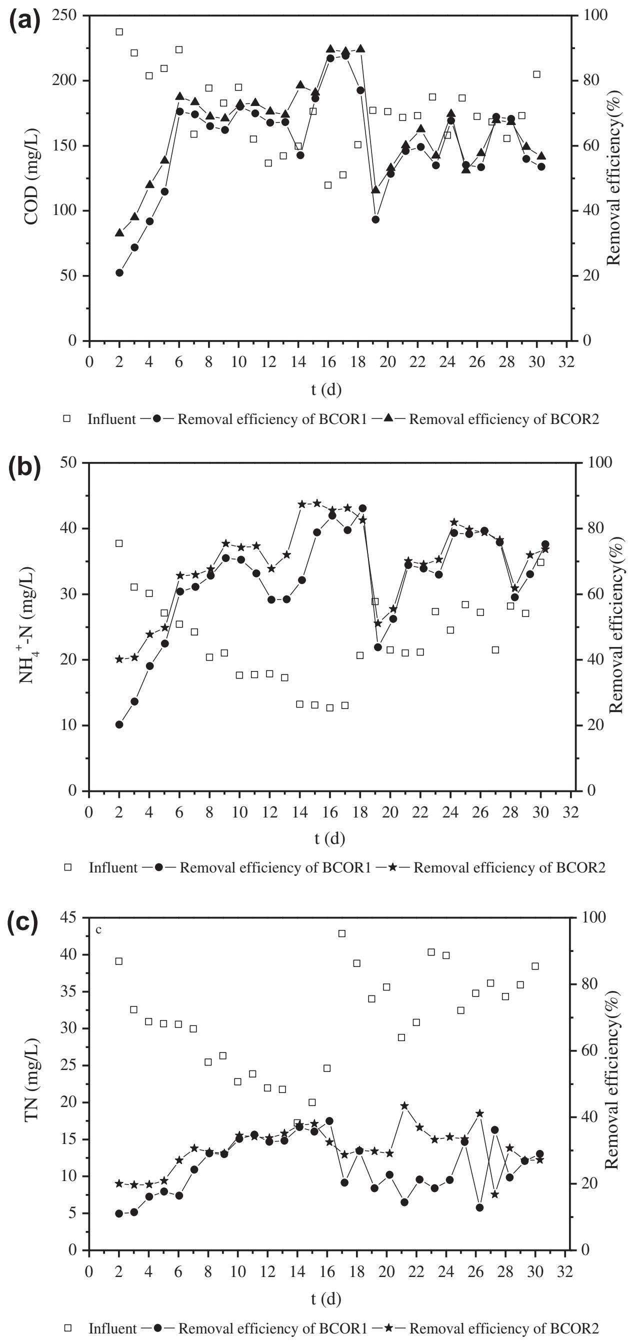

Fig. 4. Comparison of BFBC and combined carrier for the removal of COD (a), NH_4^+-N (b), TN (c), and TP (d) using BCOR.

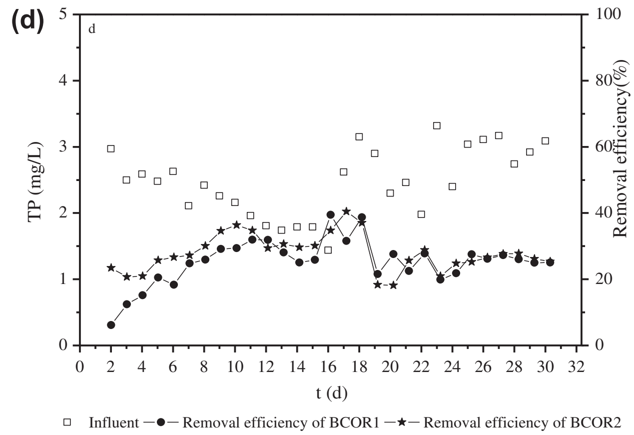

Fig. 4. (*Continued*).

phosphorus sludge discharge in the condition of aerobic. Short sludge age is considered as the premise of good performance in P removal [38]. In this trial, no sludge was discharged as the BCOR system produced less sludge, which might lead to the poor performance of P removal. In recent years, researchers have reported the biological reduction of phosphate, in which the P could be removed via phosphate → hypophosphite → phosphine [39]. Thus, biofilm reactor with prolonged sludge age without sludge discharge might realize high performance in P removal. This measure would be used to strengthen the P removal in the BCOR filled with BFBC in further studies.

3.3. Application in the upgrade of municipal sewage treatment

The COD removal efficiencies of the BCOR filled with BFBC under different HRT and its comparison with existing aeration tank were shown in Fig. 5(a). As the influent COD was among 35.0–146.7 mg/L, the effluent COD was less than 50 mg/L, reaching the class IA standard of municipal wastewater treatment plant. The COD removal efficiency showed slight decrease with the decrease of HRT. The removal efficiencies were 65.42, 63.18, 61.15, and 54.56% at HRT 15, 13, 10, and 8 h, separately. The effluent COD was apparently lower than the existing aeration tank. When the influent COD increased to 183.5 mg/L, the removal efficiency of BCOR decreased to 40.7%, almost ten times of aeration tank (4.3%), indicating the BCOR was more efficient in COD removal and resistance to COD load impact. Compared with suspended-growth activated sludge process, biofilm reactors provided greater biomass concentration, larger surface area available for reaction with the liquid, and therefore, higher resistance to hydraulic and organic load shock [40]. Hvala et al. [41] compared the performance of conventional activated sludge process and moving bed biofilm reactors, both the pilot plant and simulation experiments showed better performance of moving bed biofilm reactors than conventional activated sludge process.

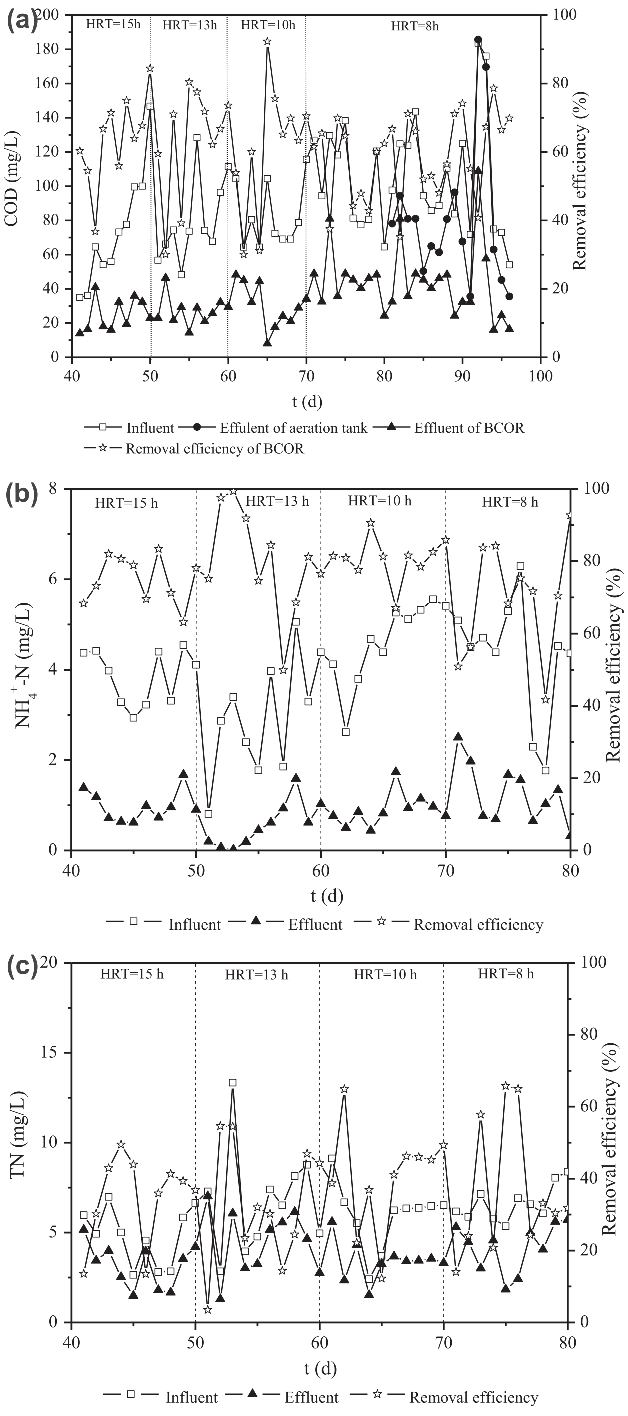

Fig. 5. Application of BCOR filled with BFBC in updegrading existing activated sludge system for removal of COD (a), NH_4^+-N (b), TN (c), and TP (d).

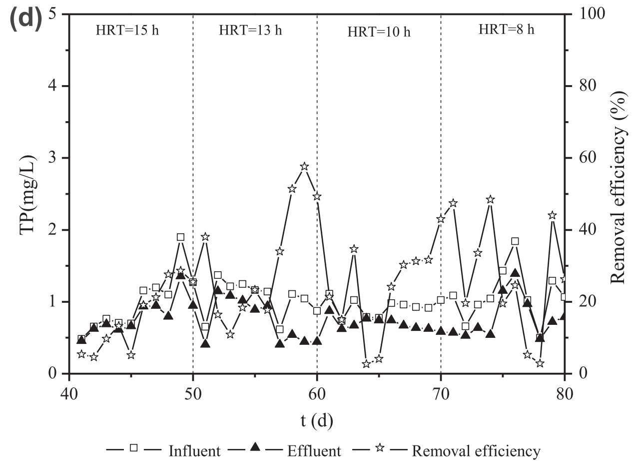

Fig. 5. (*Continued*).

The BCOR showed good performance for N removal (Fig. 5(b) and (c)). The effluent NH_4^+-N and TN were lower than 2 and 7 mg/L, respectively, reaching the class IA standard of municipal wastewater treatment plant. NH_4^+-N removal efficiencies were 74.8, 79.9, and 80.7% at HRTs of 15, 13, and 10 h, decreasing for a HRT of 8 h which gave NH_4^+-N removal efficiency of 69.5%. The poor performance observed at HRT of 8 h was attributed to the fluctuation of the influent load. The maximum removal efficiency for TN (40.2%) was observed at HRT of 10 h, which might due to the relatively steady- and low-influent TN.

As shown in Fig. 5, the P removal is comparatively lower than other pollutants. When the HRT was 15 h, the TP removal efficiency was the lowest. This result was presumably ascribed to the lower concentration and active of PAOs at the initial stage of process. The effluent TP was 0.75 mg/L, higher than the required value for class IA standard of municipal wastewater treatment. Strengthened measures should be taken to improve P removal of the BCOR such as inoculation of phosphate reduction organisms and controlled dissolved oxygen in further trials.

4. Conclusions

A novel biofilm carrier BFBC with bamboo fiber as raw materials was prepared. The specific surface area of BFBC was 5,393 m^2/m^3, significantly higher than conventional carriers made from polypropylene, polystyrene, and polyester fiber. It could be soaked completely in water in 30 min. The increase of bamboo fiber in BFBC could enhance its adsorption capacity for NH_4^+-N and P. The biofilm formed more rapidly on the BFBC than conventional combined carrier. The removal efficiencies of BCOR2 for COD, N, and P were significantly higher than BCOR1 during the start-up period. The BCOR2 showed better tolerance to the pollutants load fluctuations either. Compared with the existing activate sludge system of the municipal wastewater treatment, the BCOR filled with BFBC demonstrated higher removal efficiency for COD, and all the effluent COD, NH_4^+-N, and TN meet class IA standard of municipal wastewater treatment plant. However, the BCOR had poor performance for P removal. Further trial would be required in strengthening P removal via inoculating phosphorus reduction organisms, and adjusting the dissolved oxygen.

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