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Tertiary treatment of textile wastewater with combined media biological aerated filter (CMBAF) at different hydraulic loadings and dissolved oxygen concentrations

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ABSTRACT

An up-flow biological aerated filter packed with two layers media was employed for tertiary treatment of textile wastewater secondary effluent. Under steady state conditions, good performance of the reactor was achieved and the average COD, NH_4^+–N and total nitrogen (TN) in the effluent were 31, 2 and 8 mg/L, respectively. For a fixed dissolved oxygen (DO) concentration, an increase of hydraulic loading resulted in a decrease in substrate removal. With the increase of hydraulic loadings from 0.13 to 0.78 $m^3/(m^2\,h)$, the removal efficiencies of COD, NH_4^+–N and TN all decreased, which dropped from 52 to 38%, from 90 to 68% and from 45 to 33%, respectively. In addition, the results also confirmed that the increase of COD and NH_4^+–N removal efficiencies resulted from the increase of DO concentrations, but this variation trend was not observed for TN removal. With the increase of DO concentrations from 2.4 to 6.1 mg/L, the removal efficiencies of COD and NH_4^+–N were 39–53% and 64–88%, whenas TN removal efficiencies increased from 39 to 42% and then dropped to 35%.

1. Introduction

Water resources shortage and environmental pollution are serious problems in China. In 2004, wastewater discharge amounts in textile industry were 1.5 billion tons, which accounted for 6.83% of the total discharge amounts of all industrial wastewater [1]. One of the major ways to resolve these problems is industrial and municipal wastewater reuse. However, wastewater reuse ratio in textile industry is less than 10%, which is the lowest in all industries [1]. Thus, how to save water resources and improve wastewater reuse quality is an important and necessary task for textile industry development.

Biological aerated filter (BAF) represents an attached growth process on media which are stationary during normal operation with aeration [2]. The media allow reactors to act as deep, submerged filters and incorporate suspended solids removal. As a fixed-film process, optimal conditions for the relevant microorganisms can be maintained independently of hydraulic retention times, and therefore the process has achieved high levels of nitrification, denitrification and phosphate uptake [3]. Thus, dissolved oxygen (DO) concentration has an important influence on BAF performance. DO in BAF plays a crucial role in nitrification and has negative influence on biological denitrification. DO can inhibit denitrification because oxygen functions as the electron acceptor for microorganisms over nitrate and aerobic conditions repress enzymes involved in denitrification [4]. Although high DO concentration is necessary to enhance nitrifying bacteria activity in the biofilm reactor, denitrification is inhibited by oxygen [5,6]. Accumulated nitrite also inhibits the denitrification process, reducing the effluent quality from wastewater treatment plant. Therefore, DO and nitrite are limiting factors in the denitrification process. Moreover, key factors that influence biofilm growth within BAF also have the start-up method, nutrient concentrations in wastewater, flowrate and the backwashing regime [7].

When BAF is applied to industrial wastewater treatment, media selection plays an important role in maintaining a high amount of active biomass and a variety of microbial populations. The size of a BAF medium has a strong influence on process performance and different sized media have been recommended for different applications [8]. A medium larger than 6 mm may be preferable for a roughing stage BAF prior to full secondary treatment. Meanwhile, it has been suggested that a tertiary treatment BAF should use a medium smaller than 3 mm. The intermediate size range of 3–6 mm has been designated suitable for secondary treatment BAF. The most frequently applied media includes natural zeolite, expanded clay, puzzolane particle, clayey schist, polypropylene, and so on. However, in previous studies only one of them was acted as the media used in BAF for research [9–13]. Osorio and Hontoria [14]

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selected different relative densities of plastic material and ceramic material as media to form the submerged bed in BAF. In previous works, few investigations have been done on removal organic pollutants and nitrogen simultaneously from textile wastewater with two kinds of media with near densities packed in BAF.

Granular activated carbon (GAC) has some advantages over other media in supplying microbe abundant inhabitation surface area and possessing strong adsorption capacity [15], however which is less economically viable as an only adsorbent due to the costly activation and regeneration. In addition, GAC is easier saturated when it is used for organic wastewater treatment [16], so some methods must be adopted to lighten the treatment loadings for GAC application. Ceramsite is a potential filter media for BAF. It is a non-metallic mineral with the characteristics of high porosity and large specific surface area, which is similar to GAC characteristics [17]. On the other hand, the low-cost is also one of important advantages of ceramsite application. In the combined media biological aerated filter (CMBAF), the ceramsite layer first filtrates and degrades organic matters, which can lighten the treatment loadings of GAC layer. The GAC layer adsorbs non-degradable organic matters and ensures that the effluent quality can satisfy the reuse demand. Moreover, in comparison with BAF packed with GAC, the cost of CMBAF is much lower. Thus, this paper focuses on the feasibility of removing carbon and nitrogen simultaneously in textile wastewater with ceramsite and GAC as media packed in BAF. The performance of CMBAF was assessed at steady state conditions. In addition, COD and nitrogen removal with the feasible operational parameters, such as DO and hydraulic loading were also investigated.

2. Materials and methods

2.1. Experimental setup

The overall experimental system consisted of two sets of treatment units: A–O_1–O_2 secondary bio-treatment unit and CMBAF tertiary treatment unit. The A–O_1–O_2 submerged biofilm system consisted of three reactors in series, named reactors A, O_1 and O_2, each of them was installed with fibre packing. In the anoxic stage of the A–O_1–O_2 submerged biofilm system, non-biodegradable organic matters of high molecular weight were hydrolyzed into less molecular weight organics and biodegradability of the stream was improved. After the aerobic degradation and sedimentation steps, effluent from secondary clarifier was introduced into feed tank as the CMBAF influent.

Table 1
Characteristics of ceramsite and GAC

Media	Size range (mm)	Density (kg/m^3)	Specific surface area (m^2/g)
Ceramsite	2–3	740–790	3.99
GAC	1–2	460–510	960

Fig. 1 shows an aerobic, up-flow, submerged BAF reactor employed for this study. The cylindrical reactor made of polymethyl, had a volume of 15.7 L, a diameter of 0.1 m with a height of 2 m. The diameter of the reactor is nearly 50 times of filter media to limit the wall effect [18]. The reactor was provided with five ports located at heights of 20, 40, 60, 80 and 100 cm, respectively, allowing for liquid sampling and for measuring the head losses during filter operation. The BAF was packed with combined media of 1 m in height, which were ceramsite of 0.5 m in height and granular activated carbon of 0.5 m in height. The characteristics of ceramsite and GAC are listed in Table 1. The air was introduced into the reactor with a micro-bubble air diffuser located on the downside inlet and air flowrate was controlled with an air flow meter. One pump drove the direct up flow of wastewater through the reactor with influent entering at the base and the treated effluent left near the top.

2.2. Wastewater characteristics

The feed water was textile wastewater treated by the secondary bio-treatment of A–O_1–O_2 submerged biofilm system. The characteristics of feed wastewater are listed in Table 2.

2.3. Operational conditions

The feed wastewater was introduced to the CMBAF with a metering pump and treated by multi-function of ceramsite and GAC adsorption, microbial degradation and mechanical filtration. Hydraulic loadings were controlled in the range of 0.13–0.78 m^3/(m^2 h). In order to investigate the influence of DO concentration on the CMBAF performance, 2.4–6.1 mg/L of DO concentrations were tested with hydraulic loading of 0.39 m^3/(m^2 h). Backwashing was carried out to avoid filter clogging because of the accumulated SS and the excess biomass produced. The backwashing procedure was initiated when limiting head loss had developed (0.8 m-H_2O). The backwash procedure included air scour (4 min), followed by combined air scour and water backwash (5 min). The water and air backwash application rate were set at 10 and 15 L/min, respectively. All the experiments were carried out at ambient temperature 20–22 °C.

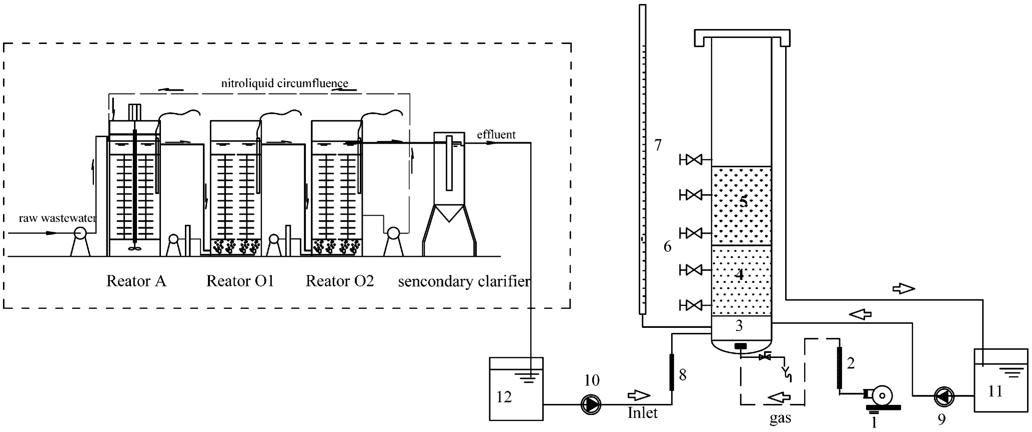

Fig. 1. Schematic diagram of the CMBAF. (1) Air compressor; (2) airflow meter; (3) support layer; (4) ceramsites layer; (5) GAC layer; (6) sampling port; (7) water level indicator; (8) liquid flow meter; (9) backwash pump; (10) feed pump; (11) backwash tank; (12) feed tank.

Table 2
Characteristics of the CMBAF influent

Item	COD	BOD	NH_4^+–N	TN	SS	pH
Influent range (mg/L)	25–121	5–21	2–12	10–19	20–50	6.5–8.0
Average (mg/L)	57	12	8	14	33	7.2

2.4. Start-up

Three methods of start-up have been reported in previous studies. Firstly, start-up of continuous reactors, initially as batch reactors followed by increasing flowrates [19]. Secondly, the use of the process liquid at either the nominal process flowrate, which was found to take 5 months [7] or increasing the flowrate from an initial low value over a period of time [19]. Finally, start-up may be carried out by seeding with activated sludge with steady state reached after 1.5 months [20]. In this study, the CMBAF was inoculated with activated sludge coming from the A–O_1–O_2 submerged biofilm system. Seeding with activated sludge required a start-up period of 15 d, including 5 d during which activated sludge was recycled. This was less than 30 d described by Mann et al. [13]. According to Faup et al. [21], seeding with activated sludge produced high suspended biomass concentration which led to improve establishment of biomass within fixed-film reactors. Subsequently one benefit was manifested of a more rapid biofilm establishment using activated sludge and resulting in more rapid increase in COD and NH_4^+–N removal efficiencies. After 15 d of the CMBAF inoculated with activated sludge, about 40% of COD removal and 60% of NH_4^+–N removal were achieved.

2.5. Analytical methods

Samples were collected every day, refrigerated at 4 °C before analysis, except for pH measurement which was done after sampling. Samples were analysed for COD, NH_4^+–N, NO_3^-–N, NO_2^-–N and TN in accordance with the standard methods [22]. Other parameters, such as pH and DO were measured with PHSJ-4A pH-meter and TWT/330 oxymeter, respectively.

3. Results and discussion

3.1. CMBAF general performance

The CMBAF fed with the effluent from the A–O_1–O_2 submerged biofilm system was performed for about 150 days. Fig. 2 illustrates concentration–time profiles of COD, NH_4^+–N and TN. As was expected, the effluent quality from the CMBAF has satisfied the standard for domestic reuse in China. As for COD, the data in Fig. 2 (a), have shown a good removal effect. COD in the influent and effluent were kept around 25–121 and 12–62 mg/L, respectively. The average COD in the influent and effluent were 57 and 31 mg/L, the average COD removal efficiency was 47%. This was higher than 30% described by Jeong et al. [23]. COD removal was attributed to the multi-function of ceramsite and GAC adsorption, microbial degradation and mechanical filtration.

The data in Fig. 2(b) show that ammonia removal was accomplished quite well through nitrification and microbial assimilation. The variation range of NH_4^+–N in the influent and effluent were 2–12 and 0–4 mg/L, and the average NH_4^+–N in the influent and effluent were 8 and 1 mg/L. Though autotrophic bacteria are easily out-competed by heterotrophic bacteria [24], nitrification efficiency in this study was still good and the average was 83%, which approached the result described by He et al. [9]. Fig. 2(b) also shows that TN varied from 10 to 19 mg/L in the influent and from 6 to 11 mg/L in the effluent. The average TN in the influent and effluent were 14 and 8 mg/L, and there was an overall reduction in TN of exceeding 40%. The mass balance would show overall loss of nitrogen, which would logically be assumed to be ammonia volatilization or through simultaneous nitrification–denitrification in the biofilm. The former could be occurred rarely since the environment in the CMBAF (e.g. pH, an average of 7.3 in the effluent, and intensity of aeration) limited the possibility of ammonia volatilization. There is evidence from this and other experimental studies that simultaneous nitrification–denitrification may have occurred within the biofilm [25–27]. Denitrification process occurs in anoxic conditions when there is enough organic matter to be used as an electron donor. Denitrification processes in BAF are limited by diffusion, mixing, biofilm thickness and availability of substrate. It was suggested by Laursen et al. [25] that nitrate removal in BAF took place deeper into the biofilm, as long as organic material was present. The depth to which oxygen can penetrate into the biofilm is determined by the bulk liquid DO concentration, the diffusion rate and the zero-order intrinsic removal rate of oxygen. In the aerobic layer, nitrate does not take part in any reactions and diffuses through the biofilm inactively. In the deeper layer, it is utilized by microorganisms for cell synthesis and growth.

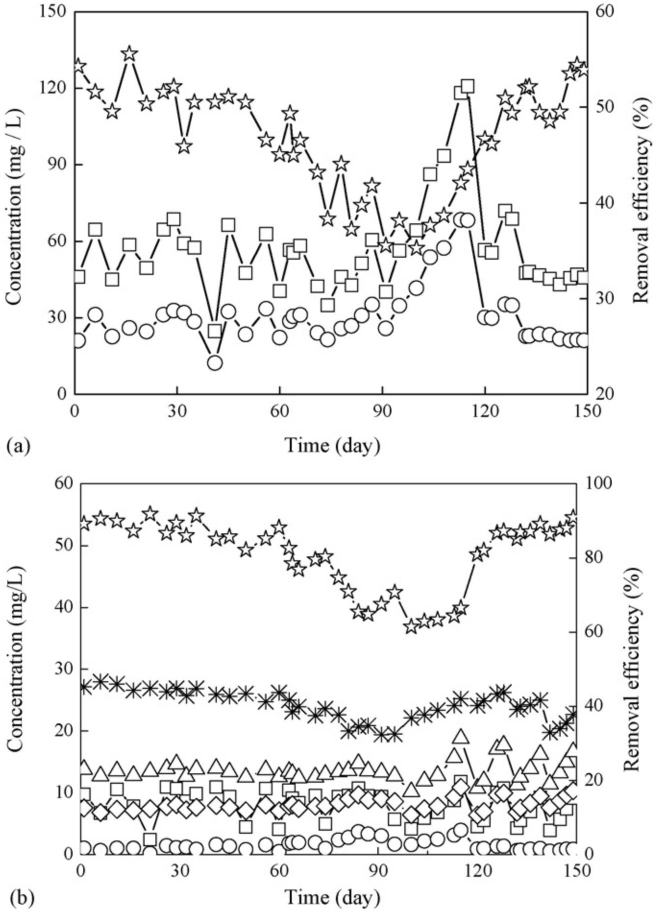

Fig. 2. (a) COD concentration in the influent and effluent of the CMBAF (COD in the influent (□); COD in the effluent (○); COD removal efficiency (☆)) (b) NH_4^+–N and TN concentration in the influent and effluent of the CMBAF (NH_4^+–N in the influent (□); NH_4^+–N in the effluent (○); TN in the influent (△); TN in the effluent (◊); NH_4^+–N removal efficiency (☆); TN removal efficiency (*)).

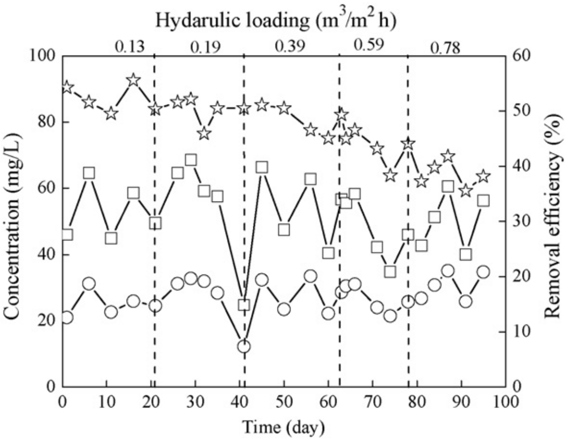

Fig. 3. COD removal at different hydraulic loadings in the CMBAF (COD in the influent (□); COD in the effluent (○); COD removal efficiency (☆)).

3.2. COD removal

3.2.1. Influence of hydraulic loading on COD removal

The CMBAF was operated at different hydraulic loadings of 0.13–0.78 $m^3/(m^2\ h)$ as DO concentration in CMBAF was kept at about 4 mg/L. Fig. 3 shows the CMBAF performance for COD removal at different hydraulic loadings. It is clearly manifested that an increase of hydraulic loading results in a decrease in COD removal for a fixed DO concentration. The average COD removal efficiencies were 52%, 49% and 38%, respectively, for hydraulic loadings of 0.13, 0.39 and 0.78 $m^3/(m^2\ h)$. These observations confirmed that hydraulic loadings could affect COD removal in the following ways: (1) increasing hydraulic loadings means shortening hydraulic retention time (HRT), so organic substrates are not fully degraded before discharged from the CMBAF; (2) increasing hydraulic loadings leads to stronger scour for media surfaces, which is also responsibly for the decrease of COD removal efficiencies.

Fig. 4 shows COD variation vs. the height of combined media bed at different hydraulic loadings. C/C_0 represented the ratio of COD concentration at each sampling port to that in the inlet. Fig. 4 clearly indicates that different hydraulic loadings result in the variation of substrate removal ratio at each height in the CMBAF. With low hydraulic loadings, i.e. 0.13, 0.19 and 0.39 $m^3/(m^2\ h)$, the substrate removal ratio was up to the maximum in the 40 cm of media bed height and then decreased with the increase of media bed height. Since organic loading is the highest at the filter inlet, which induces bacteria growth and the bioactivity attained the highest at the filter inlet. Tian et al. [28] found that TTC–DHA bioactivities decreased as the biofilter height increased, which indicated TTC–DHA activity for attached biomass varied positively to the depth of the biofilter. Within the first 40 cm media height in the CMBAF, ceramsite acted as the under-layer media. Organic substrates were captured by the ceramsite layer and then degraded by microbes in this layer. In the ceramsite layer, COD removal efficiencies of 44%, 41% and 33% have been achieved for low hydraulic loadings of 0.13, 0.19 and 0.39 $m^3/(m^2\ h)$. Within the 60–100 cm media height in the CMBAF, GAC acted as the top-layer media and played an important role in adsorbing non-degradable organic matters. As a result of most organic matters being captured and degraded by the ceramsite layer, so COD removal efficiencies in the GAC layer were lower than those in the ceramsite layer. In the 100 cm media height in CMBAF, COD removal efficiencies of 56%, 51% and 45% were achieved for low hydraulic loadings of 0.13, 0.19 and 0.39 $m^3/(m^2\ h)$.

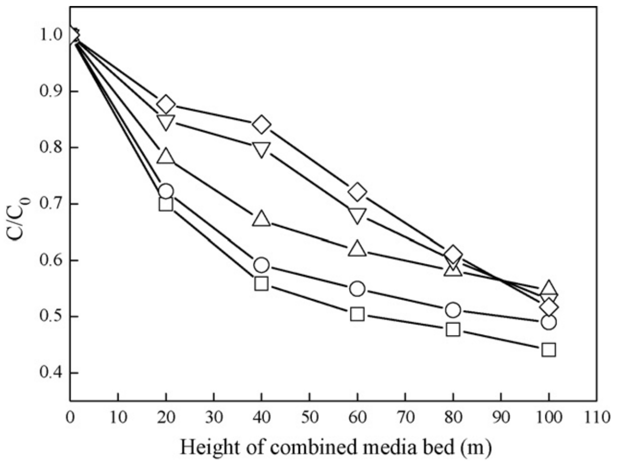

Fig. 4. COD variation at different hydraulic loadings and height of combined media (0.13 $m^3/(m^2\ h)$(□); 0.19 $m^3/(m^2\ h)$(○); 0.39 $m^3/(m^2\ h)$(△); 0.59 $m^3/(m^2\ h)$(▽); 0.78 $m^3/(m^2\ h)$(◊)).

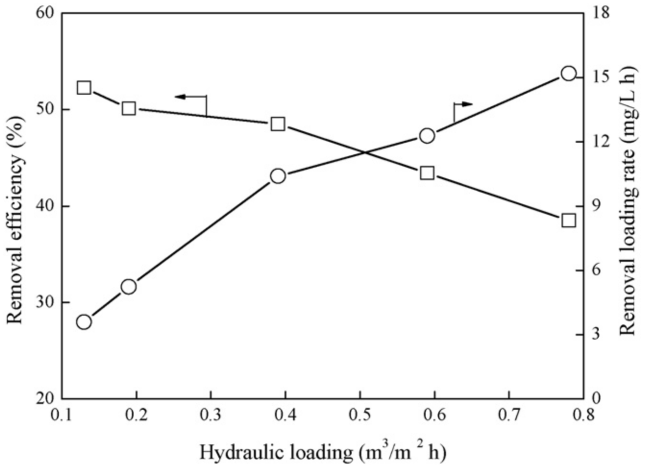

Fig. 5. COD average removal efficiencies and removal loading rates at different hydraulic loadings (average removal efficiency (□), average removal loading rate (○)).

In the case of higher hydraulic loadings (0.59 and 0.78 $m^3/(m^2\ h)$), there was an ordinal increase in substrate removal ratio with the increase of media bed height. Higher hydraulic loadings coincide with higher organic loadings, which may accelerate microbial development on the top of the CMBAF. In addition, the increase of hydraulic loading may improve substrate transfer into the biofilm [29] and remove internal diffusion limitations by controlling the biofilm thickness [30].

Fig. 5 shows the relationship between the average COD removal efficiency and average removal loading rate at different hydraulic loadings. It clearly appeared that the average COD removal loading rates increased from 3.59 to 15.19 mg/(L h), and adversely, the average COD removal efficiencies decreased from 52 to 39% in the case of hydraulic loadings varying from 0.13 to 0.78 $m^3/(m^2\ h)$. Therefore, in order to achieve good average removal efficiency and average removal loading rate simultaneously, a hydraulic loading of 0.39 $m^3/(m^2\ h)$ was the better value, in which the flow rate was 3 L/h and HRT was 1 h.

3.2.2. Influence of DO concentration on COD removal

The microbe bioactivity within the reactor was markedly influenced by DO concentration [31], so that DO concentration variation in the CMBAF resulted in COD removal variation indirectly. Fig. 6 shows the CMBAF performance for COD removal with hydraulic loading of 0.39 $m^3/(m^2\ h)$ at different DO concentrations.

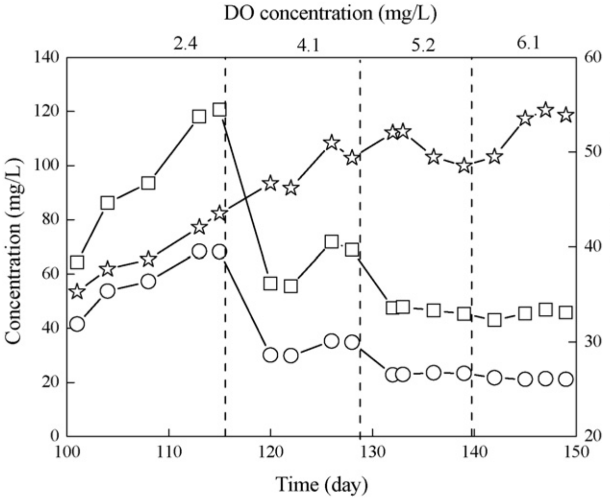

Fig. 6. COD removal at different DO concentrations in the CMBAF (COD in the influent (□), COD in the effluent (○), COD removal efficiency (☆)).

As seen from Fig. 6, different COD removal efficiencies were observed in the CMBAF when DO concentrations were increased. The average COD removal efficiencies were 39%, 48%, 51% and 53%, respectively, when DO concentrations were increased from 2.4 to 6.1 mg/L. These results confirmed that for the steady organic loading and hydraulic loading, microbe bioactivity could be enhanced, which represented as COD removal improved with the increase of DO concentrations. On the other hand, diffusion function was accordingly strengthened with the increase of DO, which also contributed for COD decrease in the effluent [32].

However, it should be noted that average COD removal efficiencies only increased 3% with DO concentration rising from 4.1 to 5.2 mg/L, but the aeration intensity was enhanced 1.5 times. So, in order to achieved good COD removal efficiency and power consumption simultaneously, the CMBAF should be operated with DO concentration of about 4 mg/L, under which average COD in the effluent was 33 mg/L.

3.3. NH_4^+–N and TN removal

3.3.1. Influence of hydraulic loading on NH_4^+–N and TN removal

The time course of NH_4^+–N and TN concentrations at different hydraulic loadings is shown in Fig. 7. DO concentration in the CMBAF was kept at 4 mg/L. For NH_4^+–N removal, the data shown in Fig. 7 indicated that the decrease of NH_4^+–N removal efficiencies was due to the increase of hydraulic loadings. The average NH_4^+–N removal efficiencies of 90%, 85% and 68% were obtained for hydraulic loadings of 0.13, 0.39 and 0.78 $m^3/(m^2\,h)$, respectively. These results were a consequence of competition between heterotrophic bacteria and autotrophic bacteria. The increase of hydraulic loading which resulted in a higher organic loading shifted a favor of heterotrophic bacteria against autotrophic bacteria contribution. In the case of substrates enrichment, heterotrophic bacteria competed with autotrophic bacteria with substrates, dissolved oxygen and inhabitation area, and accordingly which inhibited nitrification and resulted in the decrease of NH_4^+–N removal efficiencies rapidly.

For TN removal, different efficiencies were observed from Fig. 7 when hydraulic loadings were increased from 0.13 to 0.78 $m^3/(m^2\,h)$. With hydraulic loadings less than 0.39 $m^3/(m^2\,h)$, the average TN removal efficiencies were higher than 40%. These results revealed that under low hydraulic loadings, ecological structure of the microbial system kept a dynamic balance at composition and spatial distribution in the biofilm, and accordingly brought on high TN removal efficiencies. However, TN removal efficiency dropped to 33%with hydraulic loading up to 0.78 $m^3/(m^2\,h)$.

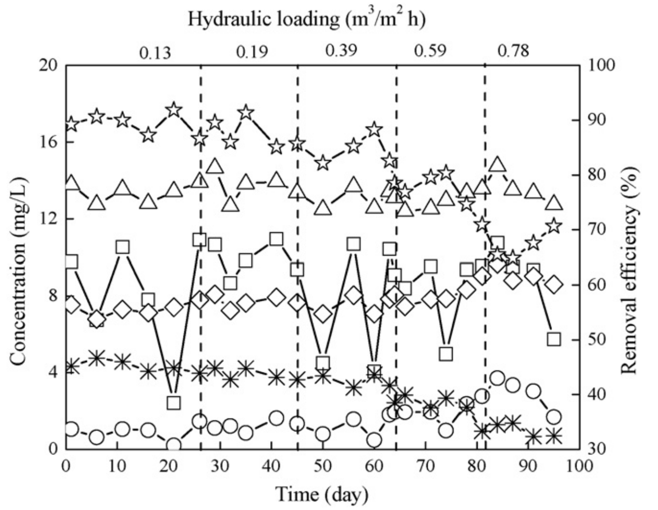

Fig. 7. Variation of NH_4^+–N and TN at different hydraulic loadings in the CMBAF (NH_4^+–N in the influent (□); NH_4^+–N in the effluent (○); TN in the influent (△); TN in the effluent (◊); NH_4^+–N removal efficiency (☆); TN removal efficiency (*)).

As mentioned above, the loss of nitrogen could be due to simultaneous nitrification–denitrification (SND) in the biofilm. The existent grads of DO and substrate concentrations result in different microenvironments formation in biofilms, which makes simultaneous nitrification–denitrification taking place in the CMBAF. SND is relevant to the amounts and activities of anaerobic microorganisms, thus SND is indirectly controlled by the thickness of anaerobic layers in biofilms. The increase of hydraulic loading led to stronger scour for media surfaces, which weakened the thickness of anaerobic layers. On the other hand, an increase of the hydraulic loading resulted in a higher organic loading, which also provided the feasibility of heterotrophic bacteria competing with autotrophic bacteria for oxygen, substrates and inhabitation area. These two aspects were all contributed to the decrease of TN removal efficiencies.

Fig. 8 reflects the variation trend of the average removal loading rates and average removal efficiencies of NH_4^+–N and TN at

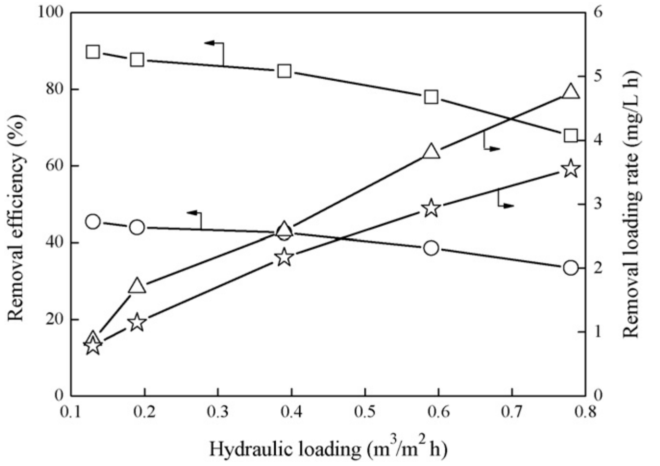

Fig. 8. NH_4^+–N and TN average removal efficiencies and removal loading rates at different hydraulic loadings (NH_4^+–N average removal efficiency (□); TN average removal efficiency (○); NH_4^+–N average removal loading rate (△); TN average removal loading rate (☆)).

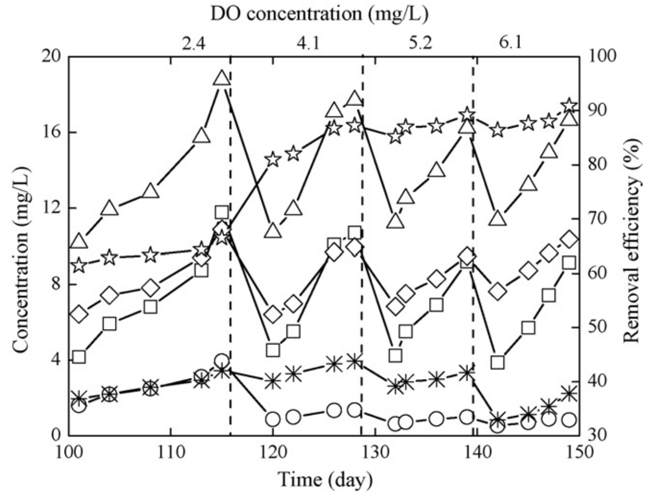

Fig. 9. Variation of NH_4^+–N and TN with different DO concentrations in the CMBAF (NH_4^+–N in the influent (□); NH_4^+–N in the effluent (○); TN in the influent (△); TN in the effluent (◊); NH_4^+–N removal efficiency (☆); TN removal efficiency (*)).

different hydraulic loadings. It appeared that there was positive correlation between the average loading rates and hydraulic loadings, but negative correlation between the average removal efficiencies and hydraulic loadings. Based on the results, a hydraulic loading of 0.39 $m^3/(m^2\,h)$ was the optimum, under which the better average removal efficiencies (85% for NH_4^+–N and 43% for TN) and average removal loading rates (2.58 mg/(L h) for NH_4^+–N and 2.17 mg/(L h) for TN) could be achieved simultaneously.

3.3.2. Influence of DO concentration on NH_4^+-N and TN removal

Fig. 9 shows that NH_4^+–N removal efficiencies increase as DO concentrations are improved. The average NH_4^+–N removal efficiencies were 64%, 84%, 87% and 88%, respectively, in the case of DO concentrations rising from 2.4 to 6.1 mg/L. DO is one of the major factors responsible for nitrification, therefore it is the limiting factor of nitrification when DO in the system is lower than that needed by bio-reactions [33]. The physiological differences between autotrophic bacteria and heterotrophic bacteria in terms of specific growth rates of up to 0.76 and 0.84 d^{-1} for ammonia and nitrite oxidizers, and 4.8 d^{-1} for heterotrophic bacteria have been reported [11]. Autotrophic bacteria compete with heterotrophic bacteria for oxygen, substrates and inhabitation area within the biofilm. Slow growing autotrophic bacteria exist in the inner part of the biofilm, making nitrification difficult, which has been corroborated by respirometric tests carried out by Lazarova and Manem [34]. Direct competition between aerobic heterotrophic bacteria and autotrophic bacteria is the main cause of the decrease in nitrifying activity [10]. DO concentrations strongly affected nitrification, and consequently affected ammonia removal. On the other hand, the increase of DO concentration continuously will result in the high power consumption and it is not useful for improving ammonia removal efficiency when DO concentrations in the CMBAF satisfy nitrification needs. This confirmed by that DO concentration was increased from 4.1 to 6.1 mg/L, but the average NH_4^+–N removal efficiency only increased from 84 to 88%.

Fig. 9 also shows that TN removal efficiencies first increased and then decreased with DO concentrations increase. The average TN removal efficiencies were 39%, 42%, 40% and 35% when DO concentrations were increased from 2.4 to 6.1 mg/L. The results confirmed that TN removal was affected remarkably by DO concentrations in the CMBAF. Denitrification produces less energy yield than oxygen respiration. Therefore, a bacterial cell growing in aerobic conditions will choose to use oxygen as terminal electron acceptor [11]. In addition to this competitive effect, oxygen controls denitrification at two levels: reversible inhibition of the activities of the denitrification enzymes and regulation of gene expression [11]. Results showed that DO concentration of 4.1 mg/L was the feasible value, with which NH_4^+–N and TN removal achieved good performances simultaneously (84% for NH_4^+–N removal and 42% for TN removal).

4. Conclusion

An up-flow biological aerated filter packed with two layers media was employed for tertiary treatment of textile wastewater secondary effluent in this study, and the results obtained are as follows:

(1) Good performance of the reactor was achieved and the average COD, NH_4^+–N and TN in the effluent were 31, 2 and 8 mg/L, which satisfies the standard for domestic reuse in China.
(2) When DO concentration in the CMBAF was kept at about 4 mg/L, the average COD removal efficiencies of 52%, 49% and 38%, the average NH_4^+–N removal efficiencies of 90%, 85% and 68%, the average TN removal efficiencies of 45%, 43% and 33% have obtained for hydraulic loadings of 0.13, 0.39 and 0.78 $m^3/(m^2\,h)$, respectively. These results are a consequence of stronger scour for media surfaces and competition between heterotrophic bacteria and autotrophic bacteria.
(3) DO concentration in the CMBAF plays a crucial role in substrate removal. The increase of DO concentrations resulted in the increase of COD and NH_4^+–N removal efficiencies, but this variation trend is not observed for TN removal. As DO concentrations were increased from 2.4 to 6.1 mg/L, the removal efficiencies of COD and NH_4^+–N were 39–53% and 64–88%, whenas TN removal efficiencies increased from 39 to 42% and then dropped to 35%. The loss of nitrogen is due to simultaneous nitrification–denitrification in the biofilm.

Acknowledgements

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