

Domestic sewage and secondary effluent treatment using vertical submerged biological filter

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Abstract. Biological filter (bio-filter) exhibits a high potential for sustainability because construction and maintenance cost are low. When bio-filters are used as pre-treatment or post-treatment technology, other treat steps in the combined treat process could prevent clogging and get better process stability and performance efficiency. This study considered bio-filters for reducing the amounts of various wastewaters, i.e., high-strength sewage, municipal wastewater and secondary effluent water, using five kinds of media. The results obtained indicate significant improvement in organics removal when influent COD are 1500 mg/L and 2500 mg/L for anaerobic and aerobic biofilters, respectively. Sufficient alkalinity would obviously improve the substrate removal in an anaerobic bio-filter, when treating high-strength wastewater. The performances of bio-filters are adequate for further removal of the residual organic material and nutrient elements for tertiary domestic wastewater treatment.

1. Introduction

Biological filters (bio-filters) are invariably cited as a low-cost and low-maintenance technology [1, 2], especially compared with conventional treatment technologies, such as activated sludge [3]. For example, it is practically impossible for activated sludge to treat low-strength wastewater with BOD lower than 20 mg l⁻¹ as the difficulty of maintaining a normal value for MLSS and conventional efficiency. Substrate-transforming microorganisms in the bio-filter are often grown as biofilm on surfaces that can be either synthetic media [4, 5], or natural media (i.e., gravel, sand, tuff, zeolite) [6, 7]. Another important advantage of microbial film process is that interference in the bio-filter is also more easily adjusted. Because bio-film reactors contain a negative feedback control system to stabilize treatment efficiency [8]. For example, If the increment of the influent loading arises, the substrate concentration on a biofilm surface will increase correspondingly and the depth of the effective layer will also increase, resulting in the suppression of the increment in substrate concentration, and vice versa. Therefore, wastewater of a wide range of strengths can be treated effectively with microbial film processes. In addition, the bio-filter exhibits a high potential for sustainability when properly



designed and maintained [9].

Bio-filters have been tested with numerous types of wastewater and it can be a valid treatment option for significant cost savings, e.g. effluent from anaerobic digesters [10, 11], nitrobenzene wastewater treated by an anaerobic baffled reactor [12], and pretreatment process for petroleum refinery wastewater [13].

It will be a dangerous risk to use secondary treated or even tertiary effluent for irrigation without disinfected for removing potential human pathogenic microorganisms. Filtration, which is regarded as one of attractive and effective processes, is usually used to remove suspended solids from wastewater effluents of biological processes to improve water quality. Therefore, Bio-filter is needed to filter effluent before discharged into the receiving waters, reused in agriculture, or utilized in body contact recreational reservoirs [14]. Bio-filters could also be applied to perform a post-treatment step for low-strength wastewater purification, e.g., secondary treatment of chromium-bearing tannery wastewaters [3], and secondary or tertiary treatment of municipal wastewater [2, 15]. The stability of bio-filter plays an important role in restraining the change of effluent water quality [16]. In order to obtain better process stability and performance efficiency, several studies have focused on combinations of anaerobic and aerobic processes for the treatment of wastewater [4, 17, 18].

The application of bio-filters should be considered to be an efficient option for reducing the amount of various wastewaters discharged into aquatic ecosystems [16]. An understanding of processes involved in pollutant removal is therefore necessary, both for improving the design and for predicting their long-term sustainability under a range of environmental conditions [19]. The objectives of this study are to evaluate the behavior of varieties of pollutant contaminants in anaerobic and aerobic bio-filters for treating wastewater at varying concentrations, i.e., high-strength domestic sewage wastewater, sewage wastewater and secondary effluent water under kinds of operation parameters, e.g. organic loading rate (OLR), hydraulic loading rate (HLR) and temperature. These results could be applied for improving the design of wastewater bio-filters and predicting their long-term sustainability for pollutant removal/reduction.

2. Material & methods

2.1. Bio-filter structure and media materials

Figure 1 shows the submerged bio-filter wastewater treatment system. The reactor consisted of a circular column with 0.48 m internal diameter and 1.2 m height. A perforated board supported the media layer from the bottom. A packing layer with a height of 0.65 m was used, and the efficient volume was 120 L. Above the packing layer there was a clay layer with a 0.20 m height for insulation and for preventing the escape of odors. The distribution and collection networks were made of perforated PVC pipe. The wastewater flowed into the reactor under the perforated board (up-flow bio-filter) by inlet pipe and was distributed by distribution pipe over the horizontal section. When the wastewater passed vertically through the packing, the biofilm could grow on a stable fixed-bed surface. After that it flowed into the collection pipe and outlet pipe. As a common filtration bed, the reactor needs backwash to maintain efficient hydraulic performance [16, 20, 21]. During these experiments, all of the bio-filters didn't clog. Therefore, they weren't backwashed.

The filter media include gravel, cinder, ceramsite, concrete block and brick. Each media has little particle size and huge specific surface area, which is good for adsorbing bacterium and high-flux for mass transfer. The layers are introduced as follows (figure 1): (1) cinder, average density of 1500 kg m⁻³, lower strength, larger porosity; (2) brick, light weight, porous; (3) broken concrete block, average density of 2890 kg m⁻³, irregular blocky of 2-4 cm, (4) biological ceramsite, average particle size of 5 mm, average density of 1500 kg m⁻³, specific surface area of 4.99 cm² g⁻¹; (5) gravel, particle size of 2-4 cm.

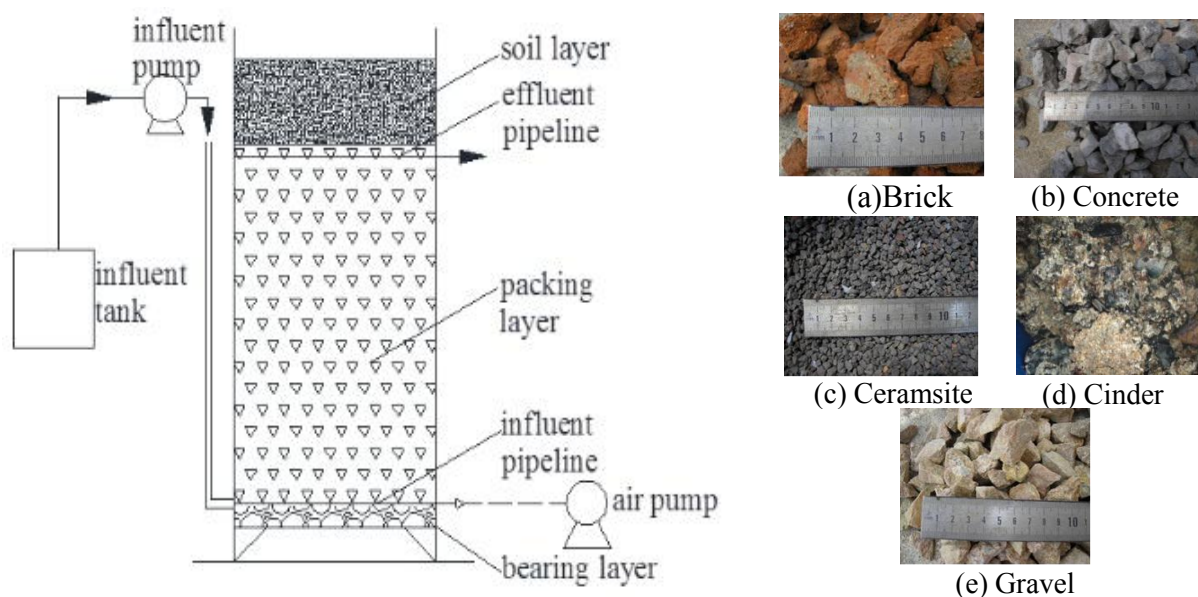


Figure 1. Diagram of experimental CW (up-flow reactor) and comparison between types of packing medium.

When the reactor is set as down-flow CW, the influent pipeline and effluent would be changed to effluent pipeline and influent, respectively. And the air pump is used for aeration which is needed in the aerobic CW. While for the anaerobic CW, the air pump is leaved unused.

2.2. Synthetic wastewater and seed sludge

The high-strength sewage and sewage was synthetic wastewater, which was mainly composed of glucose, carbamide, $(\text{NH}_4)_2\text{CO}_3$, KH_2PO_4 , K_2HPO_4 , CaCl_2 , CoCl_2 , NiCl_2 , ZnCl_2 , MgSO_4 , FeSO_4 , and NaHCO_3 . The secondary effluent wastewater and all seed sludge that was used in the experiment came from Qingdao Haibohe WWTP.

2.3. Chemical analysis

Samples were taken from the influent tank and effluent pipe each day. The concentration of $\text{NH}_4^+\text{-N}$, TN, TP, COD_{Cr} and BOD were measured by using the standard method issued by the Environmental Protection Agency (EPA) of China. The pH was detected by glass electrodes connected to a METTLER TOLEDO F25 instrument. The dissolved oxygen was quantified by a HACH HQ30d apparatus.

3. Results and discussion

3.1. High-strength sewage treatment using an anaerobic bio-filter

Two anaerobic up-flow bio-filters, in which media were ceramsite and grave respectively, were used for treating high-strength wastewater and was seeded with activated sludge. The whole experiment was divided into startup stage and formal operation stage. The startup stage wastewater mainly contained approximately 220 mg l^{-1} of glucose, 40 mg l^{-1} of carbamide, 29 mg l^{-1} of $(\text{NH}_4)_2\text{CO}_3$, and 21 mg l^{-1} of KH_2PO_4 . After the startup stage, which lasted about 55 days, the constituents in the synthetic wastewater were as follows: 1700 mg l^{-1} of glucose, 300 mg l^{-1} of carbamide, 217 mg l^{-1} of $(\text{NH}_4)_2\text{CO}_3$, 217 mg l^{-1} of K_2HPO_4 , 175.5 mg l^{-1} of KH_2PO_4 , 23.4 mg l^{-1} of CaCl_2 , 90 mg l^{-1} of MgSO_4 , 2.2 mg l^{-1} of FeSO_4 , 0.1 mg l^{-1} of CoCl_2 , 0.1 mg l^{-1} of NiCl_2 , 0.1 mg l^{-1} of ZnCl_2 , 0.12 mg l^{-1} of MnSO_4 . In the startup period, influent concentration was approximately 220 mg l^{-1} of COD. In formal operation stage, influent components increased to 1500 mg l^{-1} of COD, 900 mg l^{-1} of BOD and 110 mg l^{-1} of $\text{NH}_4^+\text{-N}$.

At the beginning of startup stage the flow rate was 20 L d⁻¹. The COD removal rates of two bio-filters began to rise sharply after day 11 and tended to be stable on day 15 (figure 2). The average COD removal rates in ceramsite and gravel bio-filters were 74.2% and 78.4%, respectively. Subsequently, flow rate was increased to 30 L d⁻¹ on day 20 and to 40 L d⁻¹ (0.075 kg-COD (m³·d)⁻¹ of OLR) on day 35. COD removal rates were maintained at 79.3% for the ceramsite bio-filter and 77.4% for gravel bio-filter.

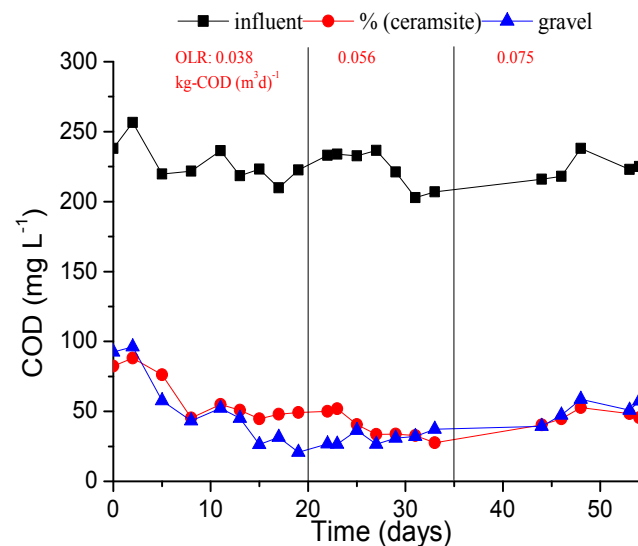


Figure 2. Startup period of anaerobic system.
The temperature is 14.2~26.5°C.

Table 1. Influence of OLR and medium on the removal rate (%) of pollution in an anaerobic reactor. The temperature is 19-23°C.

OLR (kg-COD (m ³ ·d) ⁻¹)		Startup			No alkalinity		Adding alkalinity		
		0.038	0.056	0.075	0.256	0.508	0.127	0.254	0.501
COD	ceramsite	74.2	83.5	79.3	26	28.5	83.0	78.5	73.7
	gravel	78.4	85.8	77.4	31	35.0	82.1	77.6	71.6
BOD	ceramsite	-	-	-	29.6	28.9	82.3	79.3	73.8
	gravel	-	-	-	35.2	34.9	81.5	78.6	72.1

After 55 days startup stage, the influent flow rate of wastewater was also increased as the organic material. The OLR at first was set 0.501 kg-COD (m³·d)⁻¹, six times higher than before. COD removal rates of ceramsite and gravel bio-filters were 28.5% and 35.0%, respectively (table 1). Even though OLR was decreased to 0.127 kg-COD (m³·d)⁻¹, removal rates of organic were far lower than the COD removal rates in the startup stage. Another phenomenon was that there was a net reduction in pH levels (figure 3). The influent pH was kept at approximately 7.5, but the effluent pH value decreased to only 6.2. Na₂CO₃ was added as alkalinity [22] to the influent on day 92. The Na₂CO₃ concentration varied in the experiment from 50 to 200 mg l⁻¹. The effluent pH of the two bio-filters was above 7. And the removal rates of organic recovered to above 80% in the two bio-filters after one month. As the OLR increases and HRT decreases, COD removal rate decreased from 83.0% to 73.7% for ceramsite bio-filter and from 82.1% to 71.6% for gravel bio-filter. These because that contact time between the sewage and the microbes on the biological film is shortened [23]. The trend of BOD removal rate was

same with COD. When Na_2CO_3 is not added, the removal of contaminants by the gravel bio-filter is better than the removal of contaminants by the ceramsite bio-filter (figure 4). As the alkalinity increases, the difference in the removal rate of contaminants between the ceramsite bio-filter and the gravel bio-filter gradually decreases.

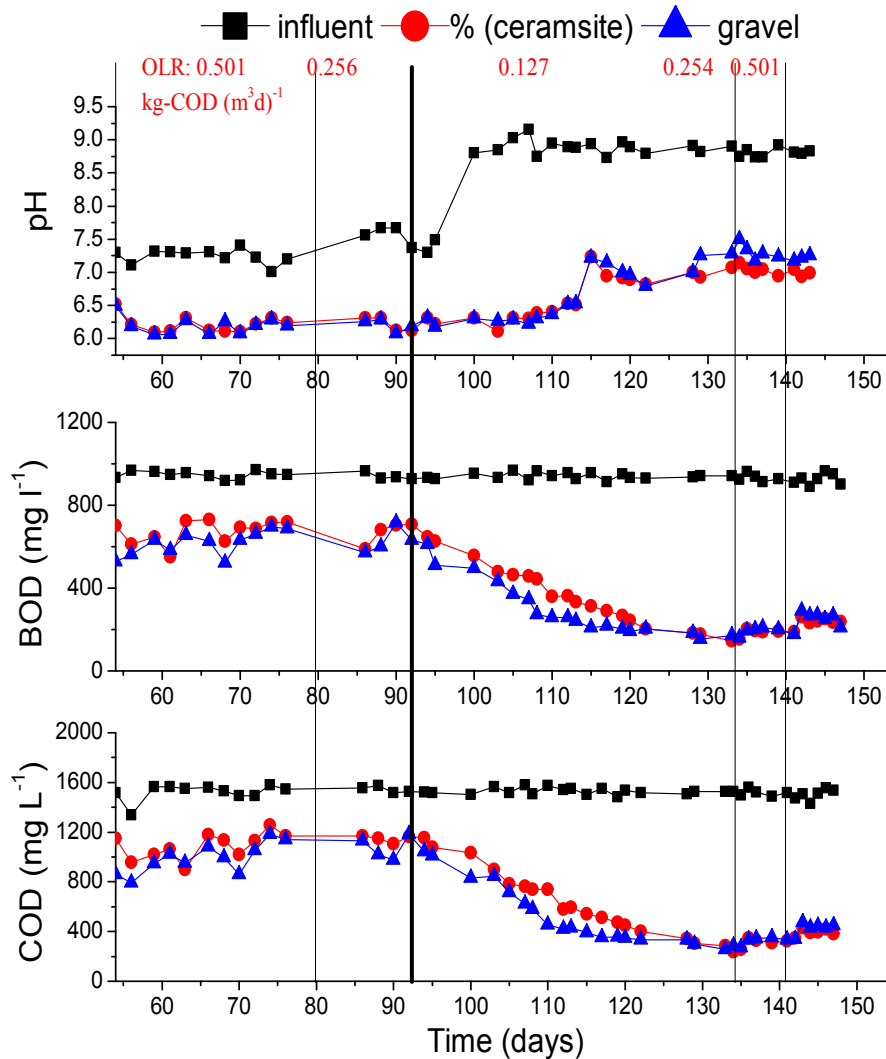


Figure 3. Overall performance of the anaerobic CW in the continuous experiment.

No Na_2CO_3 is added into the influent water before day 92. The addition of Na_2CO_3 is 200 mg l^{-1} after the day 92.

▨ influent ▨ ceramsite ▨ gravel

In this experiment, the mechanism of using the bio-filter to remove substrate from the wastewater includes precipitation adsorption [16, 23], and the degradation of microbes in the biological film, where the function of the biological film is predominant.

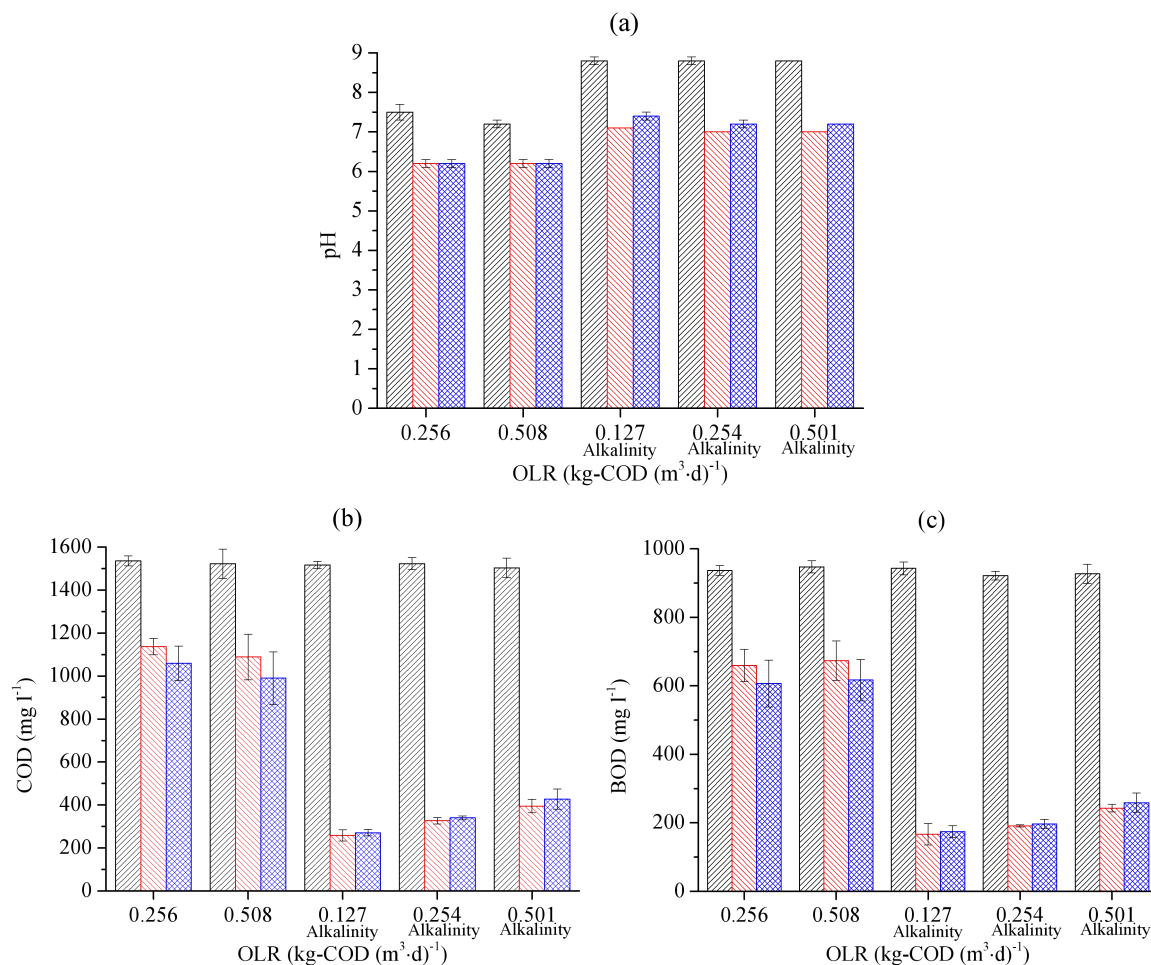


Figure 4. Influence of OLR and medium on the concentration of pollution in an anaerobic reactor. The temperature is 19-23°C.

3.2. Sewage wastewater treatment using an aerobic bio-filter

As one of the most popular domestic sewage treatment methods for small communities in rural regions, tow aerobic bio-filters with gravel as the media were used for treating municipal wastewater. The reactors were fed continuously in up-flow and down-flow modes. The air was pushed into the reactor by a micro-bubble air diffuser and the air flow rate was controlled by an air flow-meter that could provide sufficient oxygen (>2 mg/L) to ensure that the nitrifying bacteria was present. The activated sludge from the Qingdao Haibohe WWTP was further cultured during the startup stage. For continuous culture, the concentrations of influent COD and $\text{NH}_4^+\text{-N}$ in feed water were 200-500 mg l⁻¹ and 30-50 mg l⁻¹, and the flow rate was 20 L d⁻¹. The constituents in the synthetic wastewater were glucose, carbamide, $(\text{NH}_4)_2\text{CO}_3$, KH_2PO_4 , K_2HPO_4 , CaCl_2 , MgSO_4 , FeSO_4 , and NaHCO_3 . Through a pilot study of aerobic bio-filters in up-flow and down-flow bio-filter lands, we reviewed the influence of OLR and flow direction on the removal rate of COD and $\text{NH}_4^+\text{-N}$.

During the startup stage, the OLR of up-flow and down-flow bio-filters was 0.073~0.083 kg-COD (m³·d)⁻¹. After 10 days operation, the effluent COD and $\text{NH}_4^+\text{-N}$ of two bio-filters were stable, approximately 50 mg l⁻¹ and 24 mg l⁻¹, respectively (figures 5 and 6). The removal rate of substances in the aerobic up-flow and down-flow bio-filters was shown in table 2. As the OLR increased, the COD and $\text{NH}_4^+\text{-N}$ removal rates in the aerobic bio-filters were improved. When the OLR was 0.089 kg-COD (m³·d)⁻¹, the COD removal rates were at the maximum, 96.4% and 97.5% for up-flow and down-flow bio-filters, respectively, and effluent $\text{NH}_4^+\text{-N}$ was lowest, the removal rates are 52.4% and

80.7%. A negative feedback control system is contained to stabilize treatment efficiency. If the increment of the influent loading arises, the substrate concentration on a biofilm surface will increase correspondingly, so the depth from the film surface to which the substrate reaches, i.e., the depth of the effective layer, will also increase, resulting in the suppression of the increment in substrate concentration, and vice versa [8, 24]. A moderating effluence on the treatment efficiency can also be expected even though the fluctuations of loading. However, when the OLR increased further, the substrates removal rates began to drop. When the OLR was increased to $0.226 \text{ kg-COD (m}^3\cdot\text{d)}^{-1}$, the COD removal rates were reduced to about 84% and $\text{NH}_4^+\text{-N}$ removal rates were 13.1% for up-flow bio-filter and 24.5% for down-flow bio-filter. The COD removal rate of down-flow bio-filter was almost same as that of up-flow bio-filter, and the $\text{NH}_4^+\text{-N}$ removal of down-flow bio-filter was more efficient than that of up-flow bio-filter.

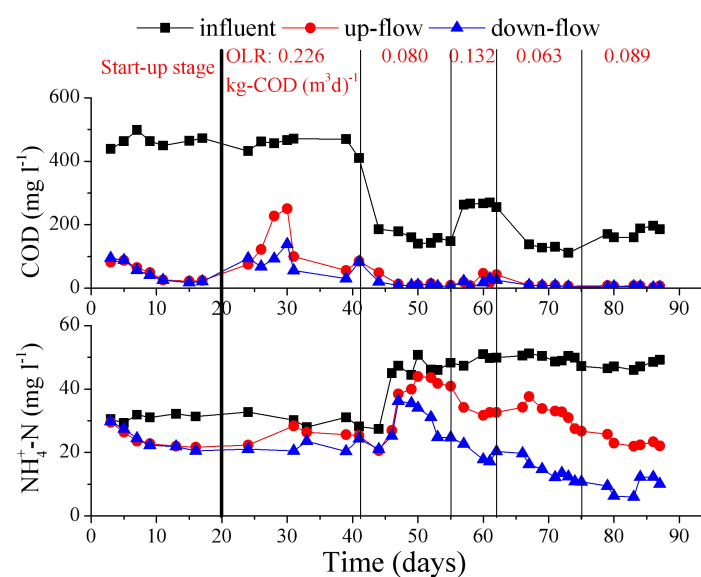


Figure 5. Overall performance of the aerobic CW in the continuous experiment.

When the OLR is $0.226 \text{ kg-COD (m}^3\cdot\text{d)}^{-1}$, because the treatment effect of the aerobic up-flow and down-flow CWs is reduced sharply, and the system is backwashed. During operation in the remaining four stages, the system is not backwashed.

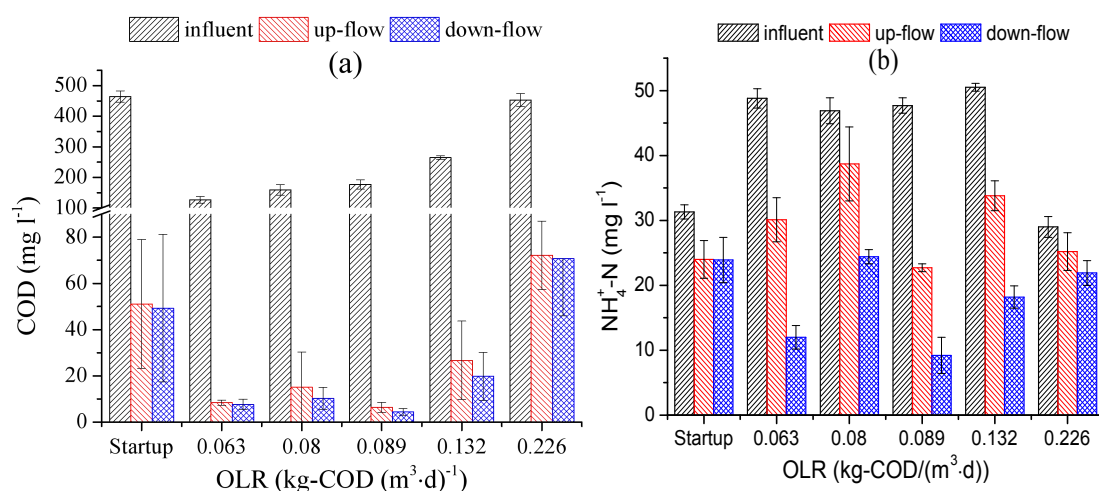


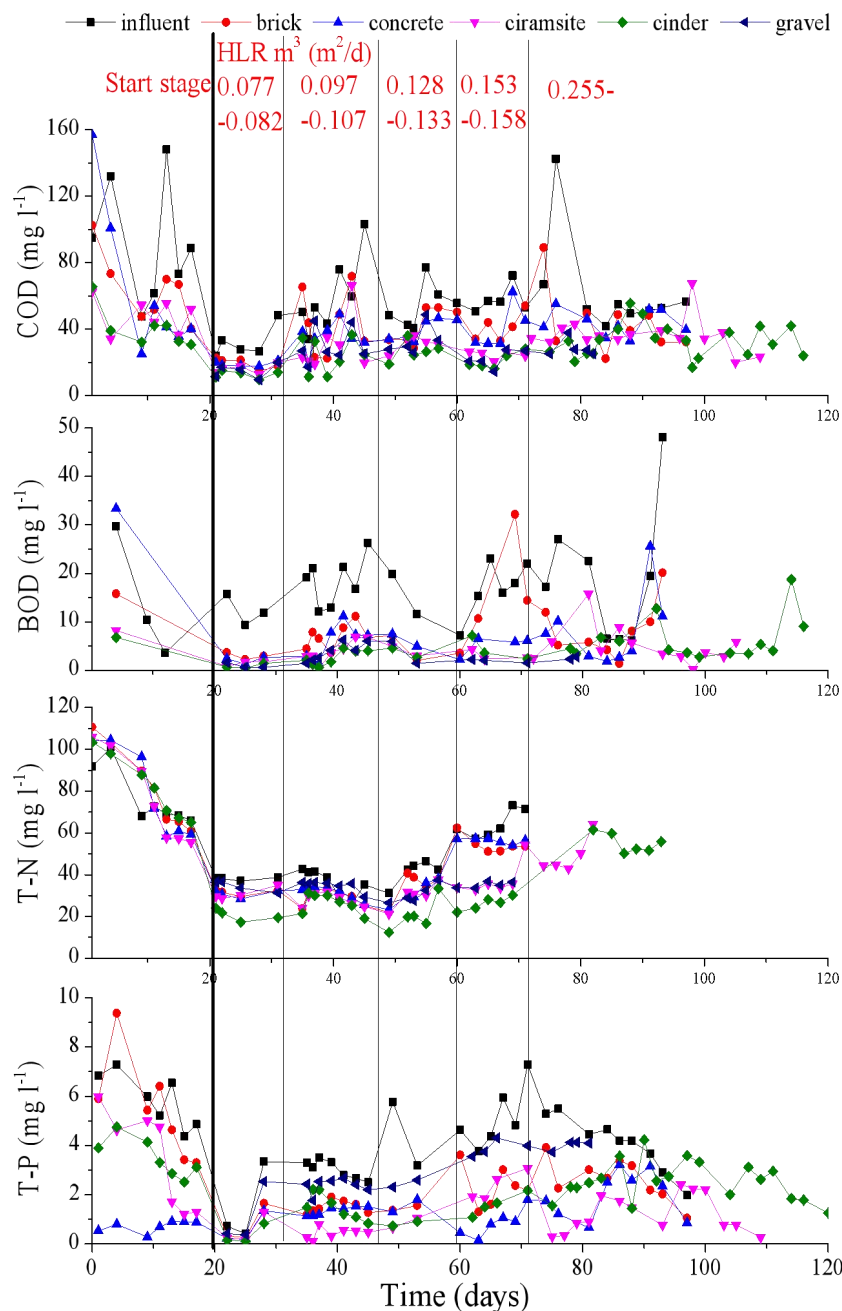
Figure 6. Effect of OLR on concentration of pollution in aerobic reactor.

The temperature is $19\text{--}26.8^\circ\text{C}$; pH is between 7.1–8.0; DO is above 2.0 mg l^{-1} .

Table 2. Effect of OLR on pollution removal rate (%) in aerobic reactor.

OLR (kg-COD (m ³ ·d) ⁻¹)		Startup	0.063	0.080	0.089	0.132	0.226
COD	up-flow	89	93.4	90.5	96.4	89.9	84.1
	down-flow	89.4	93.9	93.5	97.5	92.5	84.4
NH ₄ ⁺ -N	up-flow	23.3	38.3	17.5	52.4	33.1	13.1
	down-flow	23.6	75.4	48.0	80.7	64.0	24.5

The temperature is 19-26.8°C; pH is between 7.1-8.0; DO is above 2.0 mg l⁻¹.

**Figure 7.** Influent and effluent COD, BOD, TN and TP variation with HLR when using the secondary treatment wastewater as the influent in the anaerobic reactor.

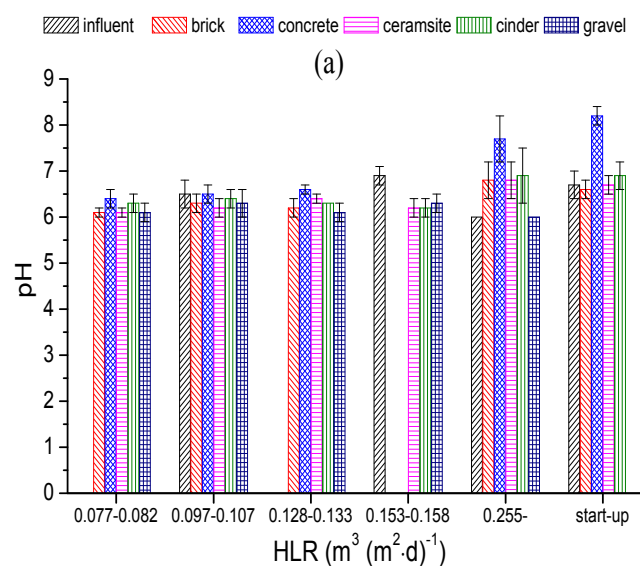
3.3. Secondary effluent wastewater post-treatment using bio-filter

Five anaerobic up-flow bio-filters were applied for treating secondary effluent wastewater with filter media of gravel, cinder, ceramsite, concrete block and brick. The influent wastewater came from settling tank effluent of Qingdao Haibohe WWTP, which was purified in this experiment. The average BOD₅/COD ratio was below 0.3, meaning low biodegradability [25]. After the film formation was successful in the startup stage, the formal operation stage began.

In the startup stage, pH values were 6.6 ~ 8.2. The flow rate was 25 L d⁻¹, and the hydraulic retention time (HRT) was 115.2 h. Influent pollution concentrations varied strongly, 86.2±37.9 mg l⁻¹ of COD, 14.6±13.6 mg l⁻¹ of BOD, 76.7±13.8 mg l⁻¹ of TN and 5.9±1.1 mg l⁻¹ of TP. The startup stage went on day 20.

After startup stage, the system entered the formal operation stage (figure 7). The amounts of removed substrates in different kinds of HRT were shown in figure 8 and table 3. When the hydraulic load was 0.077~0.270 m³ (m²·d)⁻¹, except for individual effluent water from the brick, substrate concentrations of effluent were less than 40 mg l⁻¹ COD and 8 mg l⁻¹ BOD. As the hydraulic load was increased, the ability of all bio-filters in removing the contaminants was reduced. When the HLR was 0.077~0.082 m³ (m²·d)⁻¹, the effluent COD and BOD of all bio-filters were at the maximum and decreased as the hydraulic load increased. The COD average removal rates of five bio-filters are less than 60% in 120 days. The COD removal rate of gravel bio-filter was the highest, up to 52.8%. The average removal rates of cinder and ceramsite bio-filters were 51.0% and 44.8%, respectively. The concrete and brick bio-filters' efficiencies were only 33.2% and 28.6%, respectively. For five bio-filters, the BOD average removal rate of gravel bio-filter was the highest, reaching 83.9%. The next were 76.3%, 74.4% and 65.3% for ceramsite, cinder and concrete bio-filters. The BOD removal rate of brick bio-filter was the least, only 53.5%.

As a whole, TN removal rates of all bio-filters were very low in 120 days. The cinder had the best TN removal rate, and the average removal rate was 48.1%. The ceramsite was the next, and the average removal rate was 33.1%. The average TN removal rate for gravel was 27.4%. For brick and concrete, the average removal rate was less 20%. Influent water contains only nitrate nitrogen and the trend of TN removal rate was in accordance with trend of nitrate removal [26]. Complementary organic matter and suspended solids removal can be achieved in the bio-filters as the same time, but denitrification is not always obtained (even very low loading rates are applied). The process leading to TN removal is mostly bacterial denitrification transformations, under the anaerobic conditions [27]. The denitrification efficiency of treating high-nitrate waters with low organic carbon has been shown that it depends on C:N ration, and the peak efficiency occurs at C:N ration>5:1 [28-30]. So the total



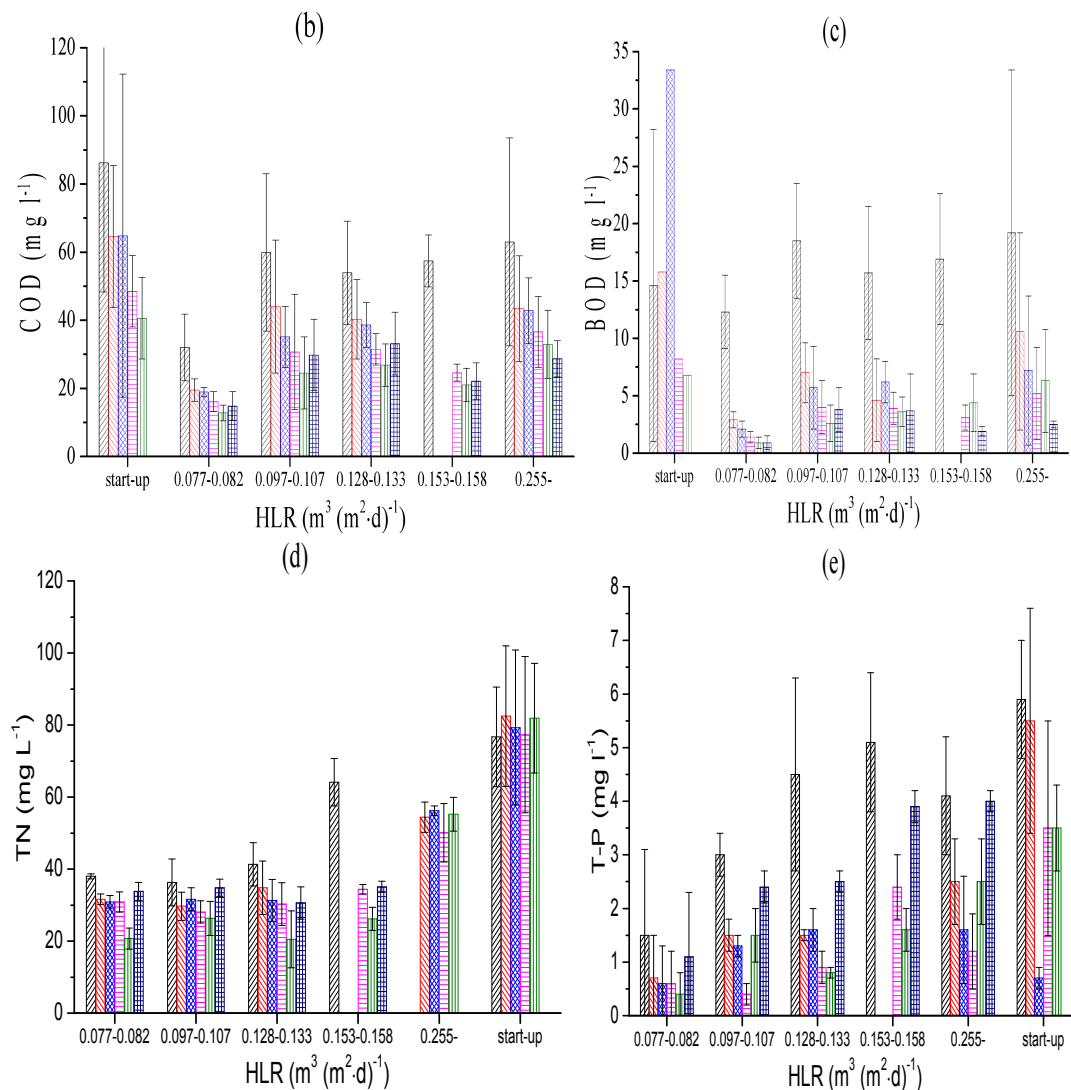


Figure 8. Concentration of pollution with HLR when using the secondary treatment wastewater as the influent in the anaerobic reactor. The temperature is between 22-30°C.

Table 3. Removal rate (%) of pollution with HLR when using the secondary treatment wastewater as the influent in the anaerobic reactor.

HLR (m³ (m²·d)⁻¹)		Startup	0.077-0.082	0.097-0.107	0.128-0.133	0.153-0.158	0.255-
COD	brick	25.1	38.8	26.6	25.4	-	31.1
	concrete	24.8	40.9	41.3	28.4	-	32
	ceramsite	43.7	49.7	48.7	41.7	57.2	42
	cinder	52.9	60.1	59	50.2	63.5	47.8
	gravel		53.7	50.2	38.7	61.6	54.5
BOD	brick	-8.2	76.3	62.1	70.7	-	44.6
	concrete	-111	82.9	69.5	60.4	-	62.4
	ceramsite	75.4	88.6	78.2	75.1	81.6	73.1
	cinder	17.1	93.1	85.9	76.9	74.1	67.1

TN	gravel	-	92.5	79.4	76.5	88.5	86.8
	brick	-7.6	16.9	18.2	15.9	-	-
	concrete	-3.4	18.7	13	24.2	-	-
	ceramsite	-0.8	18.7	22.6	26.7	46.4	-
	cinder	-6.8	45.7	27.7	50.5	59	-
TP	gravel	-	11.1	4.2	25.9	45.2	-
	brick	6.4	50.1	50.5	67.3	-	38.4
	concrete	87.8	60.4	55.6	65.3	-	61.7
	ceramsite	40.1	61.5	85.3	81	53.8	69.8
	cinder	40.1	75	49.3	81.6	68.7	37.7
	gravel	-	25.8	21.7	45.2	24.1	1.8

The temperature is between 22-30°C.

nitrogen reduction depended on the condition of the secondary effluent. However, the organic content in the influent is sufficiently low and not easily biodegradable. The bulk DO profiles decreases along height of column and the highest DO concentration was achieved at the bottom. Therefore, the removal of BOD occurs mainly in the influent part instead of denitrification. Denitrification would be inhibited due to insufficient electron acceptors even other conditions are suitable. These are also reasons that no significant negative or positive correlation between HLR and purification efficiency were found.

The phosphorus removal rates of ceramsite and concrete bio-filters were the best, and the average values were 70.7% and 63.0%, possibly due to the higher specific area of the ceramsite and its capacity to adsorb TP [7]. The cinder and brick bio-filters' efficiency were 48.7% and 47.7%, respectively. The phosphorus removal rate for the gravel was the worst, and the average removal rate was 24.4%. The low flow rate leads to higher rate of phosphorus sorption due to long contact time. However, as table 3 calculated, the effect of HLR on the phosphorus removal wasn't significant and systematic differences detected, which partly was caused by the fluctuation of influent [31].

One reason for TP removal is that the necessary anaerobic and aerobic condition for phosphate accumulating organisms was not formed in this system, which is not the main function for TP removal in this study because influent COD is relatively low and enough biodegradable substrates aren't available [20]. The major function of phosphorus removal is strongly influenced by forced precipitation and adsorbing [32, 33]. The different conditions in the bio-filter with kinds of media caused the variance removal of TP. For chemical precipitation, it needs suitable metal ions, appropriate DO and pH conditions to form insoluble substances, such as hydroxyapatite, a calcium phosphate compound [34]. Otherwise, other studies have shown that some materials are not like static adsorbent, and they may change reactive surface to influence their ability of phosphorus removal [6]. In Healy's opinion, through a filter's lifetime, the adsorption capacity decreases as the phosphate sorption sites become saturated, which is a challenge for bio-filter maintain and long-term operation [35].

4. Conclusions

This study shows that biological filters are an alternative technology for removing nutrient material from both high and low-strength sewage and secondary effluent. The substrate removal rate increases significantly after Na₂CO₃ was added in the influent of anaerobic bio-filter. In the aerobic bio-filters for treating sewage, when the OLR was increased to 0.089 kg-COD (m³·d)⁻¹, the COD removal rates were at a maximum of 96.4% and 97.5% for up- and down-flow reactors, respectively. The removal rate of NH₄⁺-N was reduced as the OLR is increased. The removal rate of substrate in the aerobic down-flow bio-filter was almost same as in the up-flow bio-filter.

When bio-filters with gravel, ceramsite or cinder as media were used for treating secondary

effluent, more than 70% of BOD could be remove. But TN removal was poor. Along the entire bio-filter profiles, gravel and cinder bio-filters had a higher ability to remove organic materials; the ceramsite bio-filter exhibits better performance in phosphorus removal. The application of bio-filter should be considered to be an efficient alternative for reducing the amount of various wastewaters discharged into aquatic ecosystems.

Acknowledgments

This project was supported by BUCT Fund for Disciplines Construction and Development (Project No. XK1506). The authors gratefully acknowledge the trust and support of all the members of the research team.

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