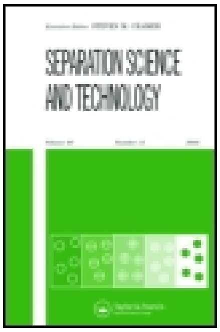

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Operation of Fixed-bed Bioreactor for Polluted Surface Water Treatment

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Abstract: Dissolved organic matters and ammonia nitrogen are serious contaminants of surface water in Taiwan. These contaminants can interfere with the water treatment process and cause biological instability in the finished water. One solution is to employ a biological treatment stage prior to the conventional water treatment process. A continuous flow biological filter packed with reticulated PU foam was used to remove ammonia nitrogen and organic materials before the conventional water treatment practice. The effect of its operation mode, namely, empty bed contact time (EBCT) and backwash, on the removal efficiencies of ammonia and organic matter was examined. The results suggested that ammonia nitrogen and organic nitrogen can be effectively removed by controlling the operation mode of the biological fixed bed. Efficient ammonia nitrogen removal was achieved upon the combination of the backwash mode with short EBCT or extended EBCT without the backwash. Efficient organic nitrogen and DOC removals were observed at short EBCT without the backwash. This study provides insights into the function of biofiltration, which benefits the design of a fixed-bed bioreactor for the treatment of polluted surface water.

Keywords: Ammonia nitrogen, biofiltration, fixed-bed bioreactor, water treatment

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INTRODUCTION

Currently in Taiwan, surface water supplies about 70% of water usage while the other 30% was provided by groundwater. However, since very little sewage treatment plants have been established in southern Taiwan up to now, some water sources have been contaminated by human, livestock, and industrial wastes. Many Asian countries are facing similar but more serious problems than the rest of the world. Polluted water sources normally contain ammonia nitrogen and small organic molecules which cannot be satisfactorily removed by a coagulation process (1, 2). In Taiwan, the most popular method for dealing with ammonia is prechlorination, by which the ammonia was oxidized to nitrogen gas. Unfortunately, prechlorination results in the generation of carcinogenic trihalomethanes (THMs) in the treated water. One potential alternative is to employ a biological process prior to the conventional water treatment processes (3). The best practice is biological filtration which has been used in Europe, United States, China, and Taiwan (4). Biological treatment has been considered a potential alternative for removing ammonia nitrogen and small organic molecules because of its effectiveness and low operation cost (5). Moreover, biological treatments prior to conventional process can enhance the performance of coagulation/sedimentation (6). Most biological treatments are operated in a fixed-bed bio-film mode for the carrier can adsorb and store large amount of microbes to maintain a stable treatment (4, 7). Another advantage of placing the biological unit in front of the coagulation treatment is that it eliminates the prechlorination and reduces the generation of disinfection-by-products (DBPs) as well as lowering the coagulant dosage for the subsequent treatment process (8, 9).

When a fixed-bed bio-film is used as a pretreatment process for polluted surface water treatment, large quantities of inorganic particles and microorganism will accumulate in the biological reactor, which blocks the filter bed and affects its function (10). Nitrification is a more important issue with bio-pretreatment for polluted surface water treatment. Same research has found that the performance of nitrification of a bioreactor for wastewater treatment can be effected by operation modes (10, 11). Most studies regarding bio-pretreatment in polluted surface water treatment have mainly focused on the removal efficiencies of ammonia and the precursors of THMs (7, 12–14). Very little study examined the effect of biofiltration and its operation. Since nitrifying bacteria grow slowly, it is necessary to immobilize them on a carrier to prevent a wash-out (15). Reticulum polyurethane foam (PU foam) has a high specific surface area which can reach 2400 m^2/m^3, and a porosity of 97% (16). It appears to be an excellent colonization matrix to biofiltration. To achieve satisfactory organic and ammonia removal, the operation pattern of the bioreactor must be well defined. The aim of this study was to determine the effects of operation modes and backwash on the removals of ammonia nitrogen and organic materials by a highly porous biological fix-bed.

MATERIAL AND METHODS

The raw water was sampled and collected from the Chi-Shui River in southern Taiwan. The river water has been contaminated by the upstream discharge of farming, industrial, and domestic wastes. The characteristics of the polluted water, namely, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, dissolved organic carbon (DOC), and ultraviolet absorbance (UV_{254}), was analyzed.

Fixed-Bed Biological Treatment System

The pilot-scale biological treatment unit was installed in the Hsin-Ying Water Purification Plant. The system was comprised of a mixing tank and four equal-size reactors (Reactor 1, 2, 3, and 4) in series. Under the flow condition of the pilot plant testing, each reactor had an EBCT of 15 min. Therefore, the pilot plant set-up allows the operation of various EBCT times of 15, 30, 45, and 60 minutes, respectively. The raw water was pumped from the Chi-Shui River into the mixing tank. The flow rate was controlled by a peristaltic pump at a constant rate of 160 mL/min, attaining an EBCT of 15 min in each reactor. Four different EBCTs of 15, 30, 45, and 60 min were expressed as T1, T2, T3, and T4. For example, in the test of 45 min of EBCT, the raw water is pumped through the first third reactors, and the biofilter effluent was sampled from the outlet at the top of Reactor 3. Each tank was provided by air at 3 L/min to keep dissolved oxygen higher than 2 mg/L. In this study, the biofiltration experiments were conducted from September to December during the dry season of Taiwan.

The biofilter utilizes the PU foam as biological media to retain a large amount of biomass in the reactor. PU foam was cut to "fan" shape particles to prevent the face-to-face effect on the mass transfer efficiency. The media has an apparent density of about 28 kg/m^3 and about 97% void fraction with a large surface area for biomass attachment and/or entrapment. The working volume of each reactor was 5.9 L, of which 60% was occupied by PU foam, resulting in an effective volume of 2.36 L. The layout of the biological treatment system and outer view of PU foam are shown in Fig. 1. The system was sampled after one month of acclimation and each run was sampled after reaching the steady state (at least one day).

A backwash system was provided to prevent the blockage of the biological filter. Two operation modes were adopted: one with daily air-purging backwash of 5 min with gas at 12 L/min, and one without backwash. The air-purging was controlled by a magnetic valve and a timer. Under normal operation, all valves were open and the air was evenly distributed among four reactors. To enter the backwash mode, three valves were closed except one which was under the backwash. The air was forced through the open valve to provide the purging for the backwash. The microbial quantity,

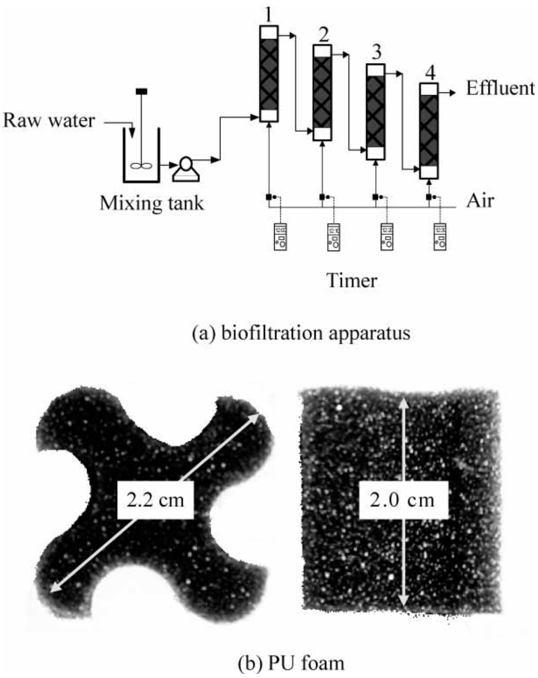

Figure 1. Schematic diagram of the biofiltration set-up and PU foam media.

ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, UV_{254}, and dissolved organic carbon (DOC) of the biological filter bed were analyzed to evaluate the effect of air-purging backwash on the function of the biological filter bed.

DOC and UV Analysis

Samples were filtered through a 0.45 μm filter paper and acidified by 6 N HCl to drop the pH to less than 2, followed by high-purity air purging for five to ten minutes. The DOC was analyzed by a SHIMADZU TOC-5000A (Japan). The UV absorbance at 254 nm (UV_{254}) and the specific ultraviolet absorbance (SUVA) value were measured to surrogate the humic acid in the water.

Trihalomethanes Analysis

Trihalomethanes were analyzed by a HP6890 Gas Chromatography with an electron capture detector (ECD). A HSS 1000 auto-injector (SCIENTIFIC HIGHTEK Co., Ltd.) was used with the Headspace as gas injector and a HP Chem Station was used to calculate the concentration.

Biomass Analysis

The procedure for biomass analysis was modified from the work by Zhang and Bishop (7), in which the biomass sample was treated with potassium sulfate to release the phosphate. The complex of ammonium molybdate and phosphate was analyzed by spectrophotometer at wavelength 610 nm.

Nitrogen Analysis

The ammonia nitrogen was determined using the Macro-Kjeldahl method. Nitrite nitrogen and nitrate nitrogen were analyzed colorimetrically at 540 nm.

RESULTS AND DISCUSSION

Raw Water Quality

The quality of the raw water is shown in Table 1. The temperature ranged from 17 to 32°C with an average of 25&°C. The pH ranged from 6.6 to 8.7. The turbidity ranged from 48.0 to 2.0 NTU with an average of 10.1 NTU. Many researchers have used the SUVA value (i.e., ratio of UV_{254} and DOC) as an index to classify the characteristics of organic substances. Edzwald and van Benschoten (17) have indicated that a SUVA larger than 4 or 5 L/mg-m, which means the organic substances in water are mostly large molecules. Table 1 showed that the SUVA of the raw water was between 1.26 and 2.92 L/mg-m with an average of 2.07 L/mg-m, implying that the natural

Table 1. Raw water quality of the Chi-Shui River

Item	Maximum	Minimum	Average (SD)
Temperature (°C)	32.1	17.10	25.1 (3.7)
pH	8.7	6.6	—
Turbidity (NTU)	48.0	2.0	10.1 (9.9)
DO (mg/L)	6.3	0.7	2.4 (1.6)
UV_{254} (cm^{-1})	0.3	0.1	0.1 (0.0)
SUVA (L/mg-m)	2.9	1.3	2.1 (0.52)
DOC (mg/L)	8.7	2.4	4.9 (1.4)
Ammonia nitrogen (mg/L)	6.9	0.1	3.0 (2.3)
Nitrite nitrogen (mg/L)	2.2	0.1	0.4 (0.4)
Nitrate nitrogen	3.1	0.2	1.9 (1.3)
THMFP (μg/L)	480	100	287 (126)

organic matter (NOM) was not the major organic pollutant in this particular water.

The DOC of the raw water ranged from 2.4 to 8.7 mg/L with an average of 4.9 mg/L. The average concentrations of the ammonia, nitrite, and nitrate nitrogen were 3.0, 0.4, and 1.9 mg/L, respectively. Both DOC and ammonia nitrogen concentrations are much higher than the standards for drinking water source, that is, 4 mg/L of total organic carbon and 1 mg/L of ammonia nitrogen. The THMFP value ranged from 100 to 480 μg/L with an average value of 287 μg/L.

Ammonia Nitrogen Removal

The average concentrations of the nitrogen contaminants of raw water and biofilter effluents under different EBCT and backwash modes are summarized in Fig. 2. The temperature (different from 3.1) of the surface water ranged from 17 to 20°C during the sampling period. As shown in Fig. 2(a), the raw water contained 3.0 mg/L ammonia nitrogen without the backwash. The average ammonia nitrogen at different EBCTs shifted from 3.0 mg/L to 1.2, 0.3, 0.1, and 0.1 mg/L ($n = 13$, n being the sampling number), respectively. Figure 2(b) shows the variation of the nitrogen contaminants with different EBCT with backwash. The average ammonia nitrogen at different EBCTs was decreased from 3.1 to 0.2, 0.2, 0.1, and 0.1 mg/L ($n = 10$), at EBCT of 15, 30, 45, and 60 min, respectively. A more significant reduction of ammonia nitrogen was observed under the air-purging backwash operation.

From Fig. 2(a), it can be calculated that the average removal efficiencies of ammonia nitrogen without the backwash were 60, 92, 96, and 97% at EBCTs of 15, 30, 45, and 60 min, respectively. However, from Fig. 2(b), the average removal efficiencies of ammonia nitrogen with the backwash were 94, 95, 96, and 97% at different EBCTs of 15, 30, 45, and 60 min, respectively. By comparing Fig. 2(a) with Fig. 2(b), the result indicated that the average removal efficiency of the ammonia nitrogen of EBCT at 30 min without the backwash was similar to that of EBCT at 15 min with air-purging backwash. Extension of EBCT brought insignificant further reduction of ammonia nitrogen. The difference between the two operation modes can be explained by the accumulated biomass and the space competition in the biological fixed-bed.

Removal of Organic Contaminants

Organic substances in water are normally represented by the UV absorbance at UV_{254} and SUVA values. The variations of UV_{254} and SUVA under different operation strategies are shown in Fig. 3. Without the backwash, as shown in Fig. 3(a), the UV_{254} was reduced by 7.5%, whereas the SUVA was increased by 10% at EBCT of 15 min. Both values increased with the increase in EBCT.

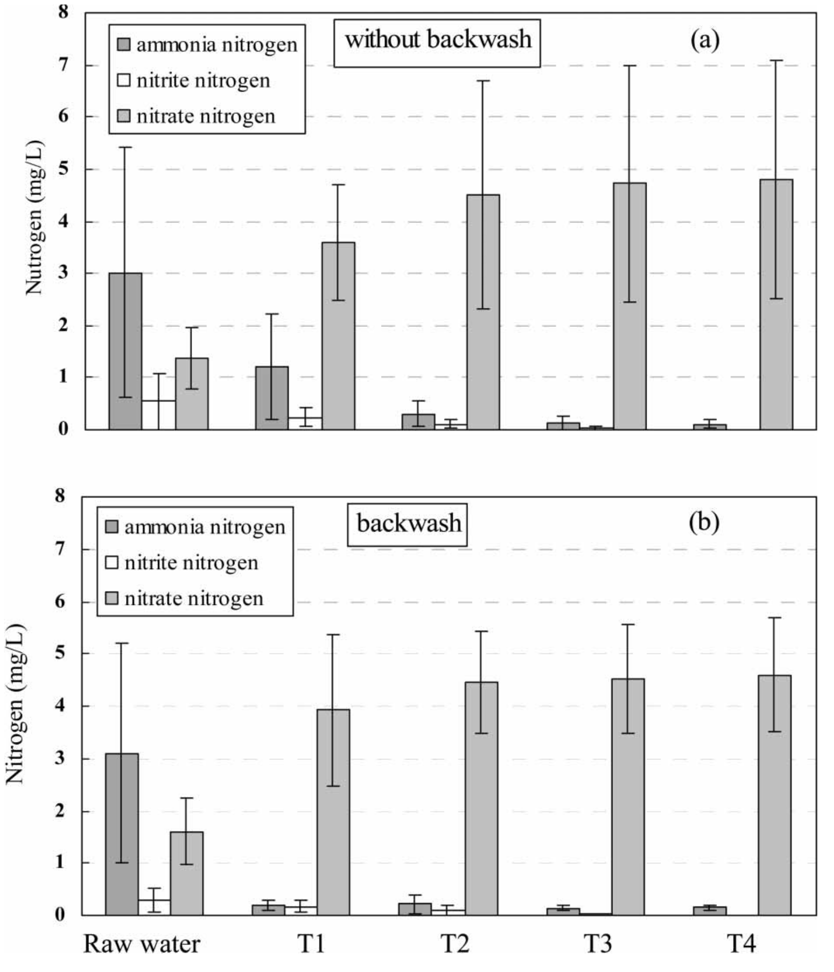

Figure 2. Relationship between EBCT and nitrogen contaminant concentration for biological fixed bed under different operation modes (a) without backwash (n = 13) (b) with air-purging backwash (n = 10).

Studies have shown that high organic removal by the coagulation/flocculation process normally occurs in water with high SUVA values (17). After the biological treatment, the SUVA value increased from 2.06 L/mg-m to 2.48 L/mg-m. Accordingly, the biological treatment process increased the coagulation/flocculation efficiency for organic substances. This phenomenon was observed under the air-purging backwash, as shown in Fig. 3(b). However, higher UV_{254} reduction and SUVA increase were generally observed in operations with backwash mode at each corresponding EBCT.

The DOC concentrations with and without backwash under different EBCTs are shown in Fig. 4. The responses of DOC concentration to EBCT

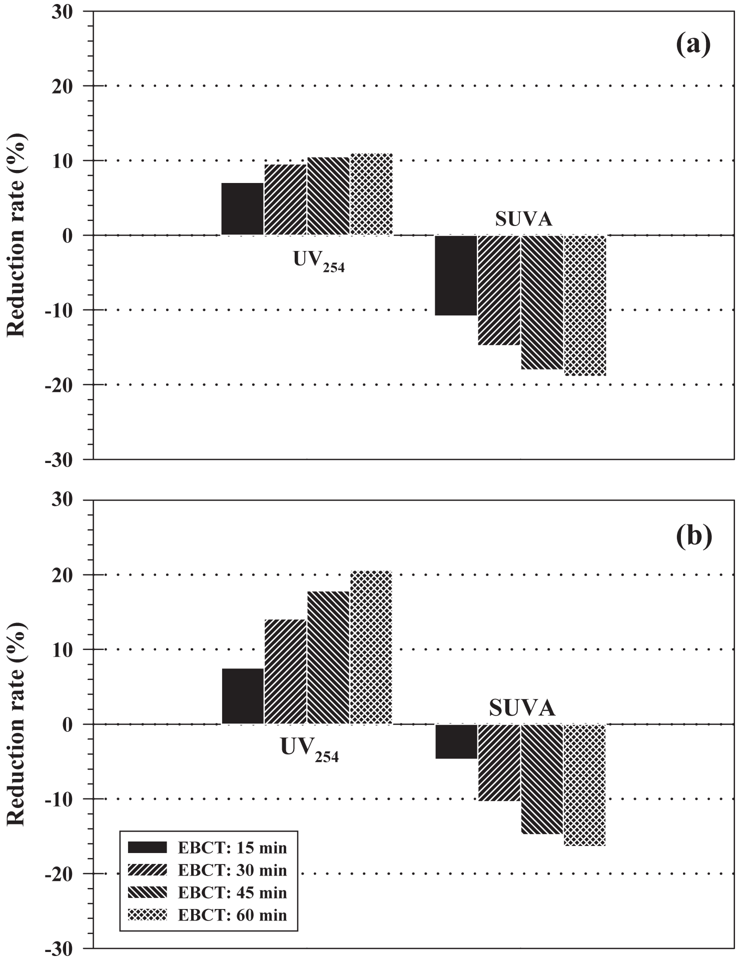

Figure 3. Relationship between EBCT and the change of UV_{254} and SUVA for biological fixed bed under two operation strategies: (a) without backwash (b) with air-purging backwash.

were quite different among these two operation modes. As shown in Fig. 4(a), the raw water contained 4.9 mg/L of DOC. The average DOC shifted from 4.9 to 4.2, 3.9, 3.7, and 3.6 mg/L ($n = 23$), at EBCT of 15, 30, 45, and 60 min, respectively. Figure 4(b) shows the variation of DOC as a function of EBCTs under the daily air-purging condition. The average DOC shifted from 4.8 mg/L to 4.6, 3.9, 3.6, and 3.5 mg/L ($n = 15$), at EBCT of 15, 30, 45, and 60 min, respectively.

From Fig. 4, it can be derived that the average removal efficiency of DOC without backwash was 18, 21, 25, and 27%, at EBCTs of 15, 30, 45, and

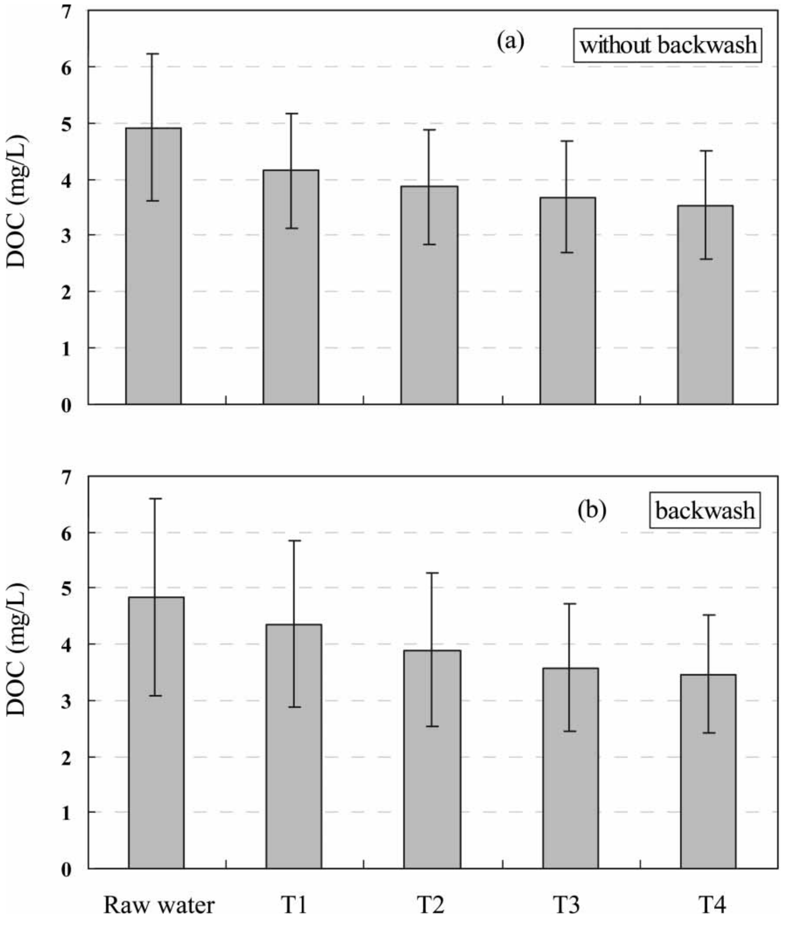

Figure 4. Relationship between EBCT and DOC concentration for biological fixed bed under two operation strategies: (a) without backwash (n = 23); (b) with air-purging backwash (n = 15).

60 min respectively. At EBCT of 15 min, the DOC of the biofilter effluent dropped from 4.9 to 4.2 mg/L, corresponding to a removal efficiency of 18%. The average removal efficiencies of DOC under the air-purging backwash at different EBCT were 12, 20, 25, and 26%, at EBCTs of 15, 30, 45, and 60 min, respectively. DOC removals without the backwash were higher at shorter EBCT (e.g., 15 min). The difference diminished with EBCT being extended. This phenomenon was also found in organic nitrogen removal, yet opposite to what was observed in ammonia nitrogen removal, as shown in Fig. 2.

The results from the pilot-operation showed that removals of ammonia-nitrogen, and DOC were significantly affected by the operation mode. For ammonia nitrogen, higher removal was achieved by the combination of the backwash and the short EBCT. Extended EBCT was required when the backwash was not applied. On the other hand, without the backwash, the EBCT must be kept short as to obtain the higher DOC removals. Since the length of EBCT is directly related to the size of the biofilter, it is crucial to decide the target pollutants before the selection of the proper operation mode.

TTHMs Formation

The effect of EBCT on total trihalomethanes (TTHMs) formation was examined. The DOC and ammonia nitrogen of the raw water and the biofilter effluents were first analyzed. The raw water contained 4.1 mg/L ammonia nitrogen and 4.6 mg/L DOC. The DOC of the biofilter effluent was 3.46 and 3.04 mg/L at EBCT of 30 and 60 minute, respectively. It is noted that the ammonia nitrogen of both the effluents was less than 0.1 mg/L. Various amount of NaOCl was added into the raw water and the biofilter effluents. After one-hour reaction at 20°C, recommended by the Standard Method 5710 (21), the TTHMs were determined. The variation of TTHMs formation with chlorine dosages was shown in Fig. 5. The chlorine residual occurring with the dose below the producing break-point consisted of chloramines rather than free chlorine. Only beyond the break-point, the residual represents free chlorine with effective disinfection ability. So in practice, we always conduct prechlorination with dosage at or beyond the break-point. The break-point chlorination for the raw water was

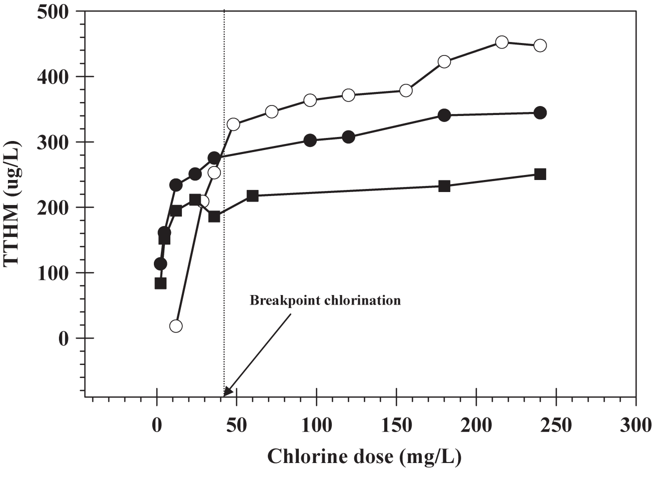

Figure 5. TTHMs formation as a function of applied chlorine for raw water and biofilter effluent. ○ Raw water: DOC = 4.61 mg/L and $[NH_3]$ = 4.12 mg-N/L, ● Effluent with EBCT of 30 min: DOC = 3.46 mg/L and $[NH_3]$ = ND, ■ Effluent with EBCT of 60 min; DOC = 3.04 mg/L and $[NH_3]$ = ND.

determined to be 40.2 mg/L; the biofilter effluent had no break-point (data not shown) in chlorination regardless of the EBCT. Figure 5 shows that for both the effluents, the TTHMs formed immediately after the addition of the sodium hypochlorite and the rate increased rapidly with the increasing chlorine dosage. The formation of TTHMs approached a constant value at chlorine dosage of 40 mg/L and 150 mg/L for effluents of 60 and 30-minute EBCT, respectively. For raw water, before the break-point, although the ammonia nitrogen reacted with chlorine first, TTHMs still formed. A similar result was found by other researchers (18). TTHMs reached constant value at chlorine dosage of 200 mg/L. Final TTHMs concentrations for raw water and biofilter effluents of 30 and 60-minute EBCT were 460, 320, and 220 μg/L, respectively. The result clearly indicated that biological pretreatment reduced the formation of TTHMs. The reduction increased with the extension of EBCT.

Biomass in the Biological Fixed Bed

Removals of ammonia nitrogen and DOC rely on the activity of microorganisms. Figure 6 shows that the biomass accumulated in biological fixed-bed varied with different operation strategy and EBCT. It is obvious that more biomass accumulated in the filter bed when no backwash was conducted. The biomass also increased with increasing EBCT. The result indicates that the amount of biomass in the biological fixed-bed can be controlled by manipulating the EBCT and the backwash.

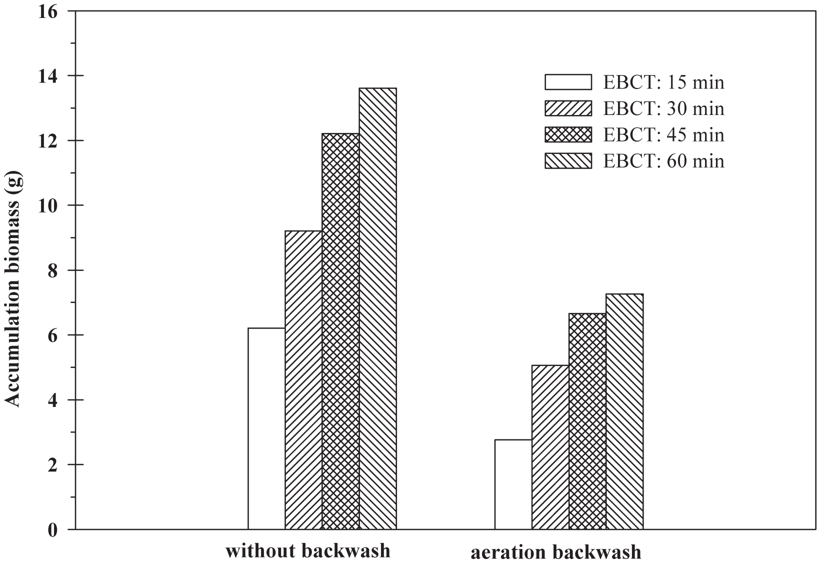

Figure 6. Relationship between accumulated biomass in a biological treatment reactor under different EBCTs and two operation modes.

Figure 2 shows that at 15-minute EBCT, the removal of ammonia nitrogen was far better when the bioreactor was operated under backwash mode. The biomass in the bed without backwash and with backwash at 15-minute EBCT were 6.0 g and 2.5 g, respectively, as shown in Fig. 6. Since the air-purging backwash was not selective to microbes, it is reasonable to assume that the same percentage of heteroterophs and nitrifiers remained in the biological fixed-bed. Therefore, the removal of ammonia nitrogen cannot be explained strictly by accumulated biomass.

The efficiency of a biological treatment system was determined by microbial activity, biomass, and mass transfer. Since the operation environment (pH and water temperature) was kept the same, the difference in ammonia nitrogen removal can be attributed to mass transfer efficiency. Researchers have proposed a space competition model for multispecies biofilm that the stratified structure affects the substrate transfer and space competition (19, 20). The accumulated solids in the biological fixed-bed included heterotrophic bacteria, nitrifying bacteria, and inorganic particles. The growth yield of nitrifying bacteria was always 4 or 5 orders lower than that of heterotrophic bacteria. Without air purging, a large amount of biomass would accumulate in the biological fixed-bed and then enhance the resistance of ammonia nitrogen transfer, resulting in the reduction of nitrification rate.

CONCLUSIONS

The following conclusions are drawn from the pilot operations:

1. Efficient ammonia nitrogen removal can be achieved at the combination of the backwash and the short EBCT. Extended EBCT was required when the backwash was not performed. Efficient DOC removals can be achieved at short EBCT without backwash.
2. Ammonia nitrogen removal was not proportional to the biomass accumulation in the biological fixed-bed. Organic substances removals, however, are proportional to the biomass accumulation.
3. Biomass accumulation in the biological fixed-bed can be controlled by EBCT and the backwash.
4. Raw water undergoing biological pretreatment increases its SUVA value as well as reduces the TTHMs formation and this reduction increases with the EBCT.

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