

**Novel membrane bioreactor (MBR) coupled with a nonwoven fabric filter for household
wastewater treatment**

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ABSTRACT

Conventional and modified membrane bioreactors (MBR) are increasingly used in small-scale wastewater treatment. However their widespread applications are hindered by relatively high costs and operational complexity. In this study, we have investigated a new concept of wastewater treatment using nonwoven fabric filter bag (NFFB) as membrane bioreactor. Activated sludge was supplied in the nonwoven fabric filter bag and the membrane filtration using the fabric filter used under gravity flow without suction pump. This study found that the biofilm layer formed inside the NFFB achieved 10 mg/L of suspended solids in the permeate within 20 min of initial operation. The dynamic biofilter layer showed a good filterability. The specific membrane resistance consisted of $0.3\text{--}1.9 \times 10^{12}$ m/kg. Due to the low F/M ratio ($0.04\text{--}0.10$ kg BOD₅/m³/d) and the resultant low sludge yield, the reactor was operated without forming excess sludge. Although the reactor provided aerobic conditions, denitrification occurred in the biofilm layer to recover its alkalinity and to avoid the need to supplement the alkalinity. This study indicates that the NFFB system provides high potential of effective wastewater treatment with simple cost-effective in rural and sparsely populated areas.

Keywords: Nonwoven fabric filter bag; Gravity filtration; Self-alkali supplement; Membrane bioreactor; Wastewater treatment

1. Introduction

The increasing discharge of untreated and poorly treated domestic wastewater in rural and peri-urban areas is growing concerns in many countries (Abegglen et al., 2008; Merok, 2008). In particular, water treatment problems associated with rural areas include the fact that they have a sparse and often dispersed population, limited finances, and limited operational expertise. Thus, a small-scale treatment system can be considered in the treatment of household wastewater (Fahd et al., 2007; Matamoros et al., 2009). However, many currently available small-scale treatment systems have limitations in providing adequate effluent quality at low cost with simple operation and maintenance. Therefore, there is an urgent demand to conduct further research into the development of a small-scale wastewater treatment system.

Conventional bioreactors coupled with microfiltration (MF) or ultrafiltration (UF) systems represent an advanced process for treating wastewater for both large (municipal) and small (household) scale demands (Abegglen et al., 2008; Lesjean and Huisjes, 2008). Modified membrane bioreactor (MBR) technologies have distinct advantages, such as the complete retention of solids, effective removal of organics and nutrients and high volumetric loading rate (Rosenberger et al., 2002; Guo et al., 2008; Yang et al., 2009; Shon et al., 2006). However, many current MBR systems employ flat or hollow fiber membrane filtration modules, which has relatively high energy consumption and require significant operational attention and alkali supplements during the operation (Jang et al., 2006a,b; Ng et al., 2006; Satyawali and Balakrishnan, 2008). Therefore, the use of established MBR technologies is limited mostly to sparsely populated rural areas.

In order to develop a more economical and simple conventional MBR system, Fuchs et al. (2005) replaced MF/UF membrane modules with a mesh filter. Earlier, Kiso et al. (2000) and Fan and Huang (2002) also used mesh filters instead of MF/UF, and eliminated suction pumping by using a gravity head in the membrane filtration of the effluent. As further

developments (Meng et al., 2005; Chang et al., 2007), nonwoven fabric filters were used instead of mesh screens, which also utilized gravity pressure for membrane filtration instead of a pump (Seo et al., 2002). These developments significantly reduced the cost of membrane separation and lowered the energy consumption, but did not address the operational and logistical problems that arose from excess sludge disposal, nor the need for an alkalinity supplement.

In this study, we investigated an improved MBR system that utilizes a cost effective nonwoven fabric filter bag as a means of providing both improved reactor volume and sludge retention. It is expected that such nonwoven fabric filter bioreactor (NFFB) systems may overcome the problems of high capital cost and significantly reduce operational and maintenance requirements. In such systems the activated sludge content of the bag could provide effective biological treatment; though the nonwoven fabric material itself can be considered a highly permeable 'rough' filter, the biofilm forming on its surface acts as an effective membrane filter that is capable of retaining small particles. Thus, with proper design, such systems would not require suction pumps or excessive sludge removal, and the need for an alkalinity supplement can be eliminated in suitable conditions for adequate operation and effluent discharge. Therefore, this concept appears to offer advantages for small-scale wastewater treatment, where low cost and operational simplicity are required.

2. Materials and methods

2.1. Operation of NFFB

The schematic diagram of the nonwoven fabric bioreactor is shown in Fig. 1. The filter bag is made of a 4-mm thick nonwoven polyester fabric, with 100 μm nominal pore size, and a specific weight of 0.71 kg/m^2 . Unlike conventional MBRs, activated sludge was seeded into the filter

bag. In the bench-scale system, the filter bag had an activated area of 0.29 m² and a reactor volume of 15 L, and a spherical air diffuser was placed at the bottom of the bag to provide aeration and sludge mixing. Since the permeability of the filter material was reduced during operation, a flexible overflow tube was fixed to the top part of the reactor to prevent possible overflow. The influent was then continuously pumped into the top portion of the reactor using an inflow pump, and the treated effluent was naturally filtered through the fabric filter into a storage space before being conveyed into a drain. The aerobic zone and the top level of outflow tubing kept the same height.

In this study, raw household wastewater was obtained from an apartment complex once or twice a day. The collected wastewater sample was stored in a refrigerator at 4 °C for at least one day, and then the sample supernatant was used as the NFFB influent. The characteristics of the settled household wastewater are listed in Table 1.

Active sludge of 5,000 mg/L MLSS was obtained from a return sludge tank in a wastewater treatment plant and seeded into the reactor, but only 3,270 mg/L MLSS was detected right after seeding because some activated sludge was attached on the surface and inside nonwoven fabric filter. The NFFB system was operated at three different hydraulic retention times (HRT) over a six-month period, with the essential parameters shown in Table 2. The volume of the reactor and filtration area was maintained constant, and the HRT was varied. It should be noted that the temperature of the reactor varied due to the ambient laboratory temperature and the values of dissolved oxygen (DO) and pH data were referred to as the aerobic reactor zone. Except for small volumes taken for analyses, no excess sludge was removed from the system over the entire operational period of 167 d.

2.2. *Measurements of water quality parameters*

Spot samples were collected from the influent, effluent, and the reactor thrice a week. The monitored parameters included biological oxygen demand (BOD_5), chemical oxygen demand (COD), ammonium (NH_4^+-N), mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), and alkalinity (AL). These analyses were carried out according to the American Standard Methods for Examination of Water and Wastewater (Eaton et al., 1998), and the suspended solids analysis was followed by the procedure of the Korean Standard Methods of Water Quality (KMOE, 2001). DO, pH, and turbidity data were obtained using YSI Model 55 DO meter, Orion Model 250A pH meter, and HF Scientific DRT-15CE turbidity meter, respectively.

2.3. *Filter autopsy of biofilm and sludge filterability*

Characteristics of the dynamic biofilm membrane that formed naturally on the wetted surface of the nonwoven fabric filter during operation were investigated using scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDX), and confocal laser scanning microscopy (CLSM). Two parallel bags without membrane cleaning cycle were used. One bag was operated in long-term experiments and the other was used to investigate the characteristics of membrane autopsy. In the SEM/EDX analyses, filter samples were cut from six different parts of the membrane filter after an initial operation of 130 min, dried overnight using a freeze dryer (IIShin Lab Co., Ltd.), and then coated with platinum for analysis in a Hitachi Model S-4700 SEM. For CLSM examinations that involved a Zeiss LSM 5 PASCAL confocal microscope, filter samples were measured from six different parts of the membrane filter after an initial operation of 130 min, and washed in pure water to separate the biofilm that had formed on the sample surface. The washing water samples were diluted, added to glass slides, and dried in the oven at 40 °C for 1 h. The dried samples were stained with 4,6-

diamidino-2-phenylindole dihydrochloride (DAPI) solution for 5 min and then washed with pure water. Thereafter, the slide was dried at room temperature in a dark container, prior to the use of microbial cell image analyses.

Activated sludge filterability was obtained using a specific cake resistance α (m/kg). This parameter was determined from Eq. 1 using a dead end filtration cell (12.5Ø, VWR brand) at constant pressure (500 mmHg) as described by Schippers and Verdow (1980).

$$\frac{t}{V} = \frac{\mu \cdot R_m}{\Delta P \cdot A} + \left(\frac{\mu \cdot \alpha \cdot C}{2\Delta P \cdot A^2} \right) \cdot V \quad (1)$$

where t is the filtration time (s), V the permeate volume (m³), μ the sludge viscosity (Pa·s), R_m the membrane initial resistance (m⁻¹), ΔP the transmembrane pressure (Pa), A the membrane surface area (m²), and C the feed biomass concentration (kg/m³).

2.4. Calculated parameters

2.4.1. Nitrogen removal via biomass uptake and denitrification

Nitrogen used for biomass synthesis was estimated using Eq. 2, based on previous research by Rittmann and McCarty (2002).

$$N_{bs} = Y \cdot BOD_5 \cdot \frac{N_b}{B} \quad (2)$$

where N_{bs} is the nitrogen used for biomass synthesis (mg/L), the yield coefficient Y with 0.49 g VSS/g NH₄⁺-N uses a C₅H₇O₂N average cell composition formula (McKinney, 1962), BOD_5 biological oxygen demand (mg/L), N_b the nitrogen in biomass (mg/L), and B the

biomass (mg/L).

Nitrogen removal during denitrification was then calculated from the total balance (Eq. 3), which included the total nitrogen (TN) removal and the nitrogen used for biomass synthesis (N_{bs}), such that

$$N_d = (TN_{in} - TN_{out}) - N_{bs} \quad (3)$$

where N_d is the nitrogen (mg/L) removed during denitrification, and TN_{in} and TN_{out} are the TN levels (mg/L) in the influent and effluent, respectively.

2.4.2. Alkalinity consumption and production

The value of the alkalinity consumption was calculated using Eq. 4, based on the alkalinity coefficient (US EPA, 1993).

$$A_c = (NH_4^+_{in} + NH_4^+_{out}) \cdot \theta_n \quad (4)$$

where A_c is the alkalinity consumption (mg/L), $NH_4^+_{in}$ and $NH_4^+_{out}$ are the ammonium concentrations (mg/L) in the influent and effluent, respectively, and the alkalinity coefficient $\theta_n = 7.1$ g/g NH_4^+-N , due to nitrification.

Finally, the alkalinity production was calculated using Eq. 5, based on the value of the alkalinity coefficient (US EPA, 1993).

$$A_p = N_d \cdot \theta_d \quad (5)$$

where A_p is the alkalinity production (mg/L), and the alkalinity coefficient $\theta_d = 3.57$ g/g NO_3^- -N, due to denitrification.

3. Results and discussion

3.1. Removal of different water quality indicators

The removal of the nonwoven filter used in the NFFB was assessed in terms of suspended solids (SS) and turbidity (Fig. 2). The initial effluent from the system was obtained immediately after charging the NFFB with the activated sludge collected from a wastewater

treatment plant. At this stage, the SS and turbidity of the effluent were relatively high with values of 26.3 mg/L and 32.5 NTU respectively. However, within 20 min of filtration, both SS and turbidity were significantly removed to 73.0% and 53.8%, respectively, indicating an exponential decrease. Further operation resulted in a minimum SS of 1.0 mg/L (96.2% removal) within 115 min and turbidity of 3.8 NTU within 130 min.

The long-term performance of the NFFB system in terms of removal of COD_{Cr}, BOD₅, NH₃, TN, TP and SS was also studied in the NFFB as shown in Fig. 3. Organic removal with the mean values at different HRTs was achieved via investigation of COD_{Cr} and BOD₅, showing removal efficiency of 85.5–89.3% and 96.7–97.9% respectively (Fig. 3A and B). Treatment of nitrogen was obtained via removal efficiency of NH₃ and TN, showing 91.9–99.4% of nitrification and 33.6–37.8% of TN removal of even in the aerobic zone of the NFFB (Fig. 3C and D). 18.3–32.3% of TP removal and 93.3–95.7% of SS injection were also achieved from the system (Fig. 3E and F).

In conventional MBR processes using MF or UF separation, only minimal or nil suspended solids can typically be detected (Xing et al., 2001; Ferraris et al., 2009). The NFFB system cannot provide similar performance due to the relatively rough filter fabric used and as indicated by the initial SS rejection. However, the results of SS rejection observed in this study were similar to the results obtained with a mesh membrane bioreactor by Kiso et al. (2000). The study reported that when 100- μ m mesh was used, the initial SS concentration in the effluent was reduced from 100 mg/L to 10 mg/L and 5 mg/L within 10 min and 40 min of operation respectively. In the system used by Fan and Huang (2002), the SS rejection was still low in spite of the use of a similar 100- μ m mesh because the initial SS concentration was higher than 1,000 mg/L in the first 2 min. Although this value rapidly decreased to less than 100 mg/L after 20 min, the final value was still higher than 50 mg/L after 120 min of filtration. The study attributed the resultant particle rejection to both the sludge cake that was

formed on the surface of the mesh and the thin gel layer that was formed in the cake. The latter layer was thought to consist of extracellular polymeric matter. In the present study, effective particle removal was achieved by using a biomass layer that was largely confined to the surface of the septum which mainly consisted of microorganisms. Considering the organic, nitrogen and phosphate removal, the system of NFFB provides similar removal efficiency than mesh coupled MBR systems (Kiso et al., 2000; Fan and Huang, 2002), but similar removal efficiency than MF/UF coupled MBR systems (Rosenberger et al., 2002; Sun et al., 2007; Abegglen et al., 2008).

3.2. *Low-pressure gravity filtration*

The NFFB process was continuously operated for 167 d without the use of a suction pump, unlike conventional (submerged) MF/UF equipped MBR systems where a suction pump is frequently used. In addition, the hydraulic head drop was found to be significantly smaller than those commonly observed in low pressure (submerged) mesh equipped MBR (Kiso et al., 2000; Fan and Huang, 2002) because the theoretical value of hydraulic head drop in the NFFB process was zero due to the same water level between the reactor and the effluent tube (Rho and Park, 2002).

The specific resistance of the cake layer is a useful indicator of sludge filterability. It is evident from Fig. 4 that the specific resistance (filterability) and the flux significantly depend on the HRT in the system. The specific cake resistance decreased at lower HRT indicating the improvement in the filterability or the flux of the NFFB. For a comparison, a conventional MBR process (Bouhabila et al., 2001) operated with 3.3 h HRT, 0.29 m³/m²/d flux, and 10–30 d solid retention time (SRT), showed a specific resistance of 3–4 × 10¹⁴ m/kg. The system presented by Rojas et al. (2005) with HRT of 8 h, 0.24 m³/m²/d flux, and SRT of 20 d showed

a maximum specific resistance of 10^{14} m/kg. However, Holakoo et al. (2007) described a system where the specific resistance was smaller than in the present system, ranging from 7.1×10^8 – 1.6×10^{10} m/kg at 4 h of HRT and 20–40 d SRT. This therefore indicates that the NFFB system could provide a relatively good filterability of activated sludge and stable performance that can be achieved over long-term operation using a reliable gravity filtration.

3.3. *Operation without excess sludge*

This NFFB system was operated without dedicated excess sludge removal during the 6-month experimental period and the SRT value was increased. Fig. 5 shows the MLSS concentration over the operational period, and its relationship to the MLVSS concentration. From the figure, it can be seen that the average concentration of MLSS slightly increased from 12 h of HRT to 10 h (from 4,420 mg/L to 4,954 mg/L), but more than doubled (to 10,436 mg/L) after the HRT was reduced from 10 h to 8 h. Here, during the operation of HRT of 12 h, the MLSS concentration was significantly fluctuated due to the generation of unknown foam. The foam was generated from 38 d to 50 d so that the concentration of MLSS was decreased from 4,700 mg/L to 1720 mg/L. However, the foam did not affect the removal efficiency. After one week intermittent seeding of the influent, the foaming disappeared and the MLSS level was stabilized.

The decrease of MLVSS with the increasing HRT can be explained by an equation of sludge production (Lawrence and McCarty, 1970; Eckenfelder et al., 1972; Lee et al., 2008) which is valid for completely mixed activated sludge systems for carbonaceous substrate removal in aerobic conditions (Eq. 6).

$$\frac{1}{\Theta_c} = \varphi \cdot \frac{S_r}{X_v \cdot t} - b \quad (6)$$

where Θ_c is the SRT (d), S_r the removed substrate (mg/L), X_v the concentration of volatile suspended solids (VSS) inside the reactor (mg/L), t the HRT (d), φ the cell yield coefficient (mg per MLVSS produced per mg of substrate removed), and b the endogenous respiration coefficient.

From Eq. 6, Eq. 7 is derived as follows, where X_v is inversely proportional to the HRT. This proportionality was observed in this MBR system, and is also predicted by models developed for a MBR system (Wen et al., 1999).

$$X_v = \frac{\varphi \cdot S_r \cdot \Theta_c}{t \cdot (b \cdot \Theta_c + 1)} \quad (7)$$

Fig. 6 presents the F/M ratios calculated from the results of BOD₅ and MLSS. The figure shows BOD loadings of 0.36-0.39 kg BOD₅/m³/d. The F/M ratio slightly decreased from 0.10 kg BOD₅/kg MLVSS/d to 0.08 kg BOD₅/kg MLVSS/d with the decrease in HRT from 12 h to 10 h. A more significant decrease to 0.04 kg BOD₅/kg MLVSS/d was observed at HRT of 8 h due to the increase of MLSS.

Sludge production and waste sludge removal are important factors in the operation of traditional activated sludge and MBR systems. Sun et al. (2007) operated a submerged MBR process for 300 d without sludge discharge and found that a low F/M ratio of 0.11 kg COD/kg MLVSS/d led to low sludge production. Ghyyot and Verstraete (1999) observed that sludge production in the submerged MBR was about 20–30% lower than in a conventional activated sludge system that used prolonged SRT. Rosenberger et al. (2002) reported that the net sludge

production of a submerged MBR was nearly zero at a low F/M ratio of 0.07 kg COD/kg MLSS/d, and thus no sludge removal was necessary during the 535 d period of their study. Kim and Yoon (2001) suggested that in the MBR system the long SRT and low F/M ratio resulted in reduced sludge production due to the effect of endogenous respiration. Considering the above results, the experimental NFFB system used a low F/M ratio and can be operated without excess sludge removal during the 6-month period of this study.

3.4. Self-alkali supplement

The NFFB system is aerobic to provide ammonia nitrification. Adequate pH for nitrification could be achieved without the provision of extra alkalinity. The results of pH and alkalinity in the NFFB effluent showed that the lowest values of pH and alkalinity were 6.5 and 33 mg/L, respectively at 12 h HRT. The maximum values of pH 7.0 and 50 mg/L alkalinity were observed at an HRT of 8 h (Fig. 7). Therefore, this system provided an ideal pH condition for nitrification which as per U.S. EPA (1993) in the pH should range from 6.5 to 8.0.

The reason that long term operation of the aerobic NFFB was possible without alkali supplementation was probably due to the fact that denitrification occurred inside the NFFB. The average value of DO detected in and out of the filter bag was 3.6 mg/L and 0.25 mg/L, respectively. Yang and Alleman (1992) reported that denitrification occurred below 0.5 mg/L of DO. The theoretical calculation of alkali production during denitrification in the NFFB are shown in Tables 3 and 4. The residual alkalinity in the effluent was theoretically calculated by three parameters: total alkali of the influent, alkali consumption during nitrification and alkali production due to denitrification (Table 4). Similar results were investigated while studying the actual alkalinity of the NFFB. Therefore NFFB can be operated normally without any alkali supplement. Actually, Im et al. (2003) showed that the treatment performance of a NFFB system

was comparable to a conventional activated sludge reactor operated without alkali supplement during the operational period (189 d). But the conventional activated sludge reactor required 100 mg/L of alkali into the aerobic zone every day because the pH value in the activated sludge reactor rapidly decreased to less than 6 if no alkali was supplemented.

3.5. *Membrane autopsy of the NFFB surface*

The characteristics of the dynamic membrane that formed on the fabric filter surface were investigated using SEM images. Fig. 8A to C shows the sample image at different magnifications. It can be seen that the NFFB was quickly clogged by the flocs. Even though the nominal pore size of the pure filter was observed to be about 100 μm (Fig. 8D), the pore size drastically reduced after contact with the activated sludge making the fabric a relatively thick membrane (Fig. 8A–C).

The mechanism of the subsequent membrane formation using the NFFB was also studied using SEM image (Fig. 9). For this analysis, the membrane sample was cut into four (approximately 1 mm thick) sections, as shown in Fig. 9A to D. The images reveal that the dynamic membrane layer was essentially limited to section 1 (Fig. 9A) of the fabric—the section that was in direct contact with the activated sludge. Some sludge particles could still be observed in section 2 (Fig. 9B) but very few particles were observed in sections 3 or 4 (Fig. 9C and D, respectively).

The composition of the biomass layer was analyzed using CLSM and SEM/EDX (Fig. 10). In the results of CLSM (Fig. 10A–D), the dominant bacterial colonies were detected (Fig. 10D), where the arrow pointed out by blue color shows bacterial colonies (Fig. 10B) and the arrow pointed out by red color shows inorganic or non-DNA organic materials (Fig. 10C). The SEM/EDX analysis (Fig. 10E) shows the overwhelming presence of organic matter. The

biomass layer was found to be composed of 47.7% carbon, 15.5% nitrogen, and 31.8% oxygen elements, for a total 95% of the overall mass.

Meng et al. (2005) showed a dynamic layer formation on surface and interspaces of the nonwoven fabric filter. They found that the surface and interspaces of the nonwoven fabric were a number of microbes. Seo et al. (2002) reported that activated sludge cake layer was formed on the surface of nonwoven fabric filter during 20 min. However, both two papers did not show a mechanism of the subsequent membrane formation and composition of the biomass layer formed on surface and interspaces of the nonwoven fabric filter.

4. Conclusions

This study investigated a scientific determination of the special performance achieved by the new concept of NFFB. We demonstrated that: 1) the nonwoven fabric filter with a biomass layer effectively removed sludge; 2) showed high sludge filterability using gravity force; 3) endogenous respiration was achieved for prolonged SRT and low F/M ratio to reduce excess sludge production; and 4) alkali production during denitrification could maintain an appropriate pH value avoiding supplementary alkali dose. Therefore these results provide an opportunity to encourage the widespread use of the NFFB system, with its low cost and simple operation for sparsely populated rural areas.

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Figures and Table Captions

Table 1. Characteristics of influent household wastewater.

Table 2. Operating conditions of the NFFB.

Table 3. Theoretical calculations of nitrogen removal.

Table 4. Theoretical calculations of alkalinity change in the reactor.

Fig. 1. Schematic diagram of the experimental NFFB system. R1 : aerobic zone with activated

sludge.

Fig. 2. Initial rejection of the nonwoven fabric filter just after initial operation of the NFFB, showing SS and turbidity.

Fig. 3. Long term removal performance of the NFFB. The influent (closed circle) and effluent (open circle) concentration of (A) COD_{cr}, (B) BOD₅, (C) NH₄⁺-N, (D) TN, (E) TP, (F) SS in the NFFB process during 167 d of continuous operation (HRT = 12: 1–62 days, HRT = 10: 63–99 days, HRT = 8: 100–167 days).

Fig. 4. Specific resistance and flux by decreasing HRT from 12 h to 8 h. The values were the means ± S.E. of more than three independent experiments.

Fig. 5. Performance of activated sludge (MLSS and MLVSS/MLSS).

Fig. 6. BOD loading rate and F/M ratio of the system.

Fig. 7. Performance of pH and alkalinity in the effluent.

Fig. 8. SEM image of membrane formation of the nonwoven fabric filter with activated sludge. (A) ×100 SEM image of the filter and sludge, (B) ×500 SEM image of the filter and sludge, (C) ×1000 SEM image of the filter and sludge, (D) control.

Fig. 9. SEM image of the section separation of the nonwoven fabric filter (×500). (A) section 1: the side directly connected with the activated sludge zone, (B) section 2: the right part after

the section 1, (C) section 3: the right part after section 2, (D) section 4: the side directly connected to the effluent zone.

Fig. 10. Composition of the activated sludge obtained from inside the nonwoven fabric filter. (A) Differential interference contrast (DIC) image, (B) DAPI staining image, (C) Auto-fluorescent image, (D) Overlap image of A, B and C in CLSM analysis of the sludge, (E) SEM and EDX results of the sludge.

Table 1.

Parameter	Concentration^{a,b}
COD _(Cr) , mg/L	286.2 ± 10.86
BOD ₅ , mg/L	148.1 ± 5.59
SS, mg/L	62.5 ± 3.26
TN, mg/L	42.7 ± 1.14
NH ₃ , mg/L	32.4 ± 0.96
pH	6.1 ± 0.07
Alkalinity, mg/L	248.7 ± 2.91

^a mean ± standard error; ^b n = 61.

Table 2.

HRT (h)	Days	Filtration area (m²)	Q_{in}(=Q_{out}) (m³/d)	Tempera- ture^{a,b} (°C)	DO^{a,b} (mg/L)	pH^{a,b}
12	1-62	0.311	0.03	16.9 ± 0.67	5.2 ± 0.21	6.2 ± 0.10
10	63-99	0.311	0.036	23.9 ± 0.56	4.7 ± 0.42	6.5 ± 0.13
8	100-167	0.311	0.045	27.1 ± 0.26	4.6 ± 0.13	6.5 ± 0.12

^a mean ± standard error; ^b n = 61.

Table 3.

Parameter	HRT		
	12 h	10 h	8 h
Removed TN, mg/L	19.3	17.0	13.5
Nitrogen for microbial synthesis, mg/L	12.7	10.3	9.1
Nitrogen by denitrification, mg/L	6.6	6.7	4.4

Table 4.

Parameter	HRT		
	12 h	10 h	8 h
Influent, mg/L	251.7	277.7	261.4
Alkali consumption by nitrification, mg/L	253.0	241.7	202.4
Alkali production by denitrification, mg/L	23.5	23.9	15.9
Theoretical alkalinity in effluent, mg/L	22.2	59.9	74.9
Detected alkalinity in effluent, mg/L	32.7	41.1	50.2

Fig. 1.

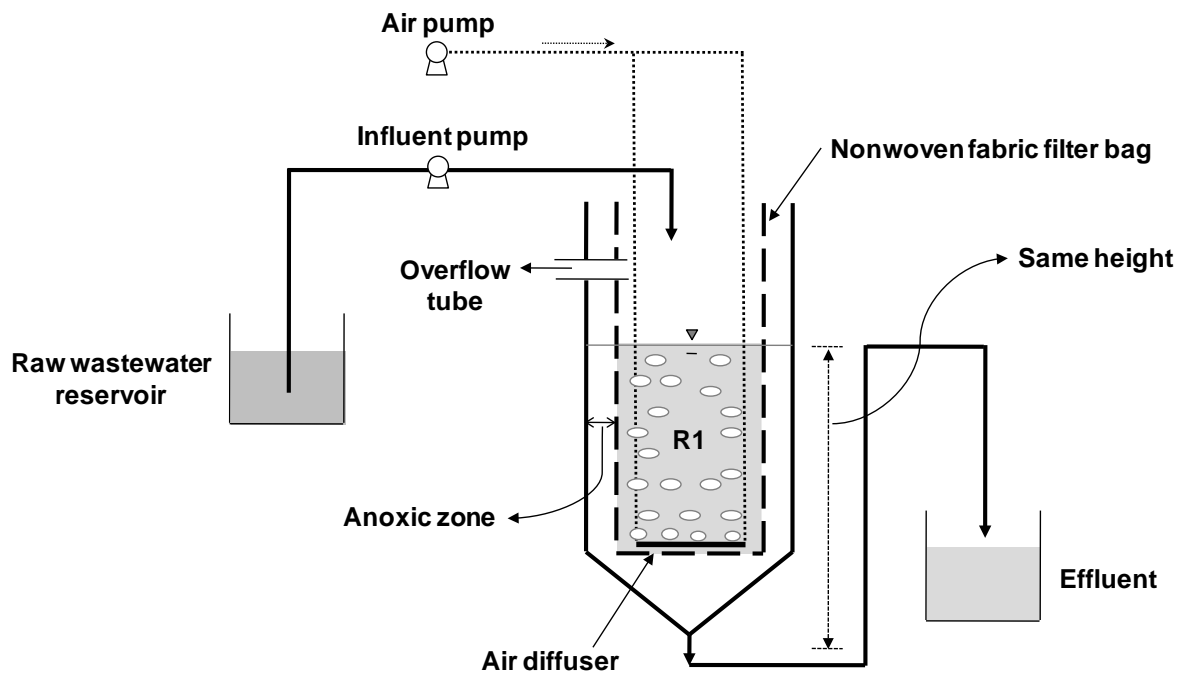


Fig. 2.

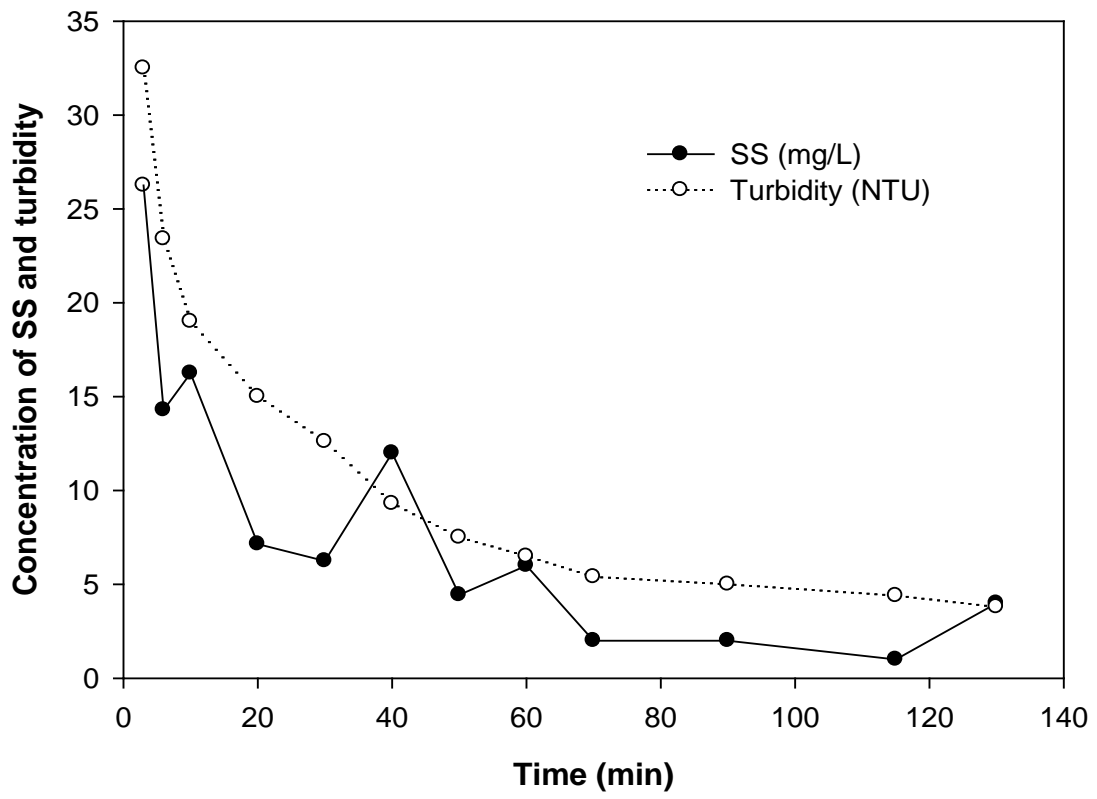


Fig. 3.

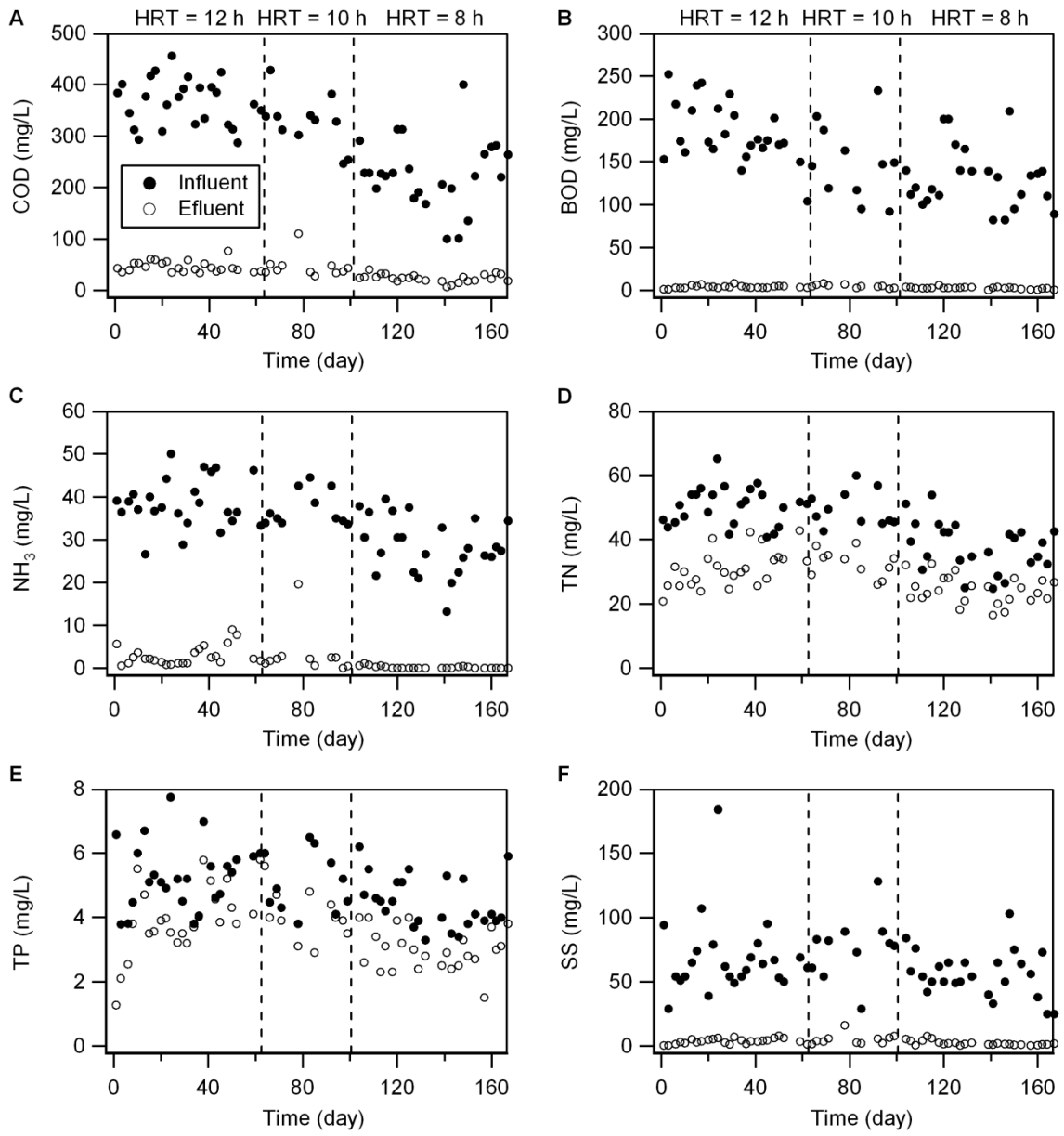


Fig. 4.

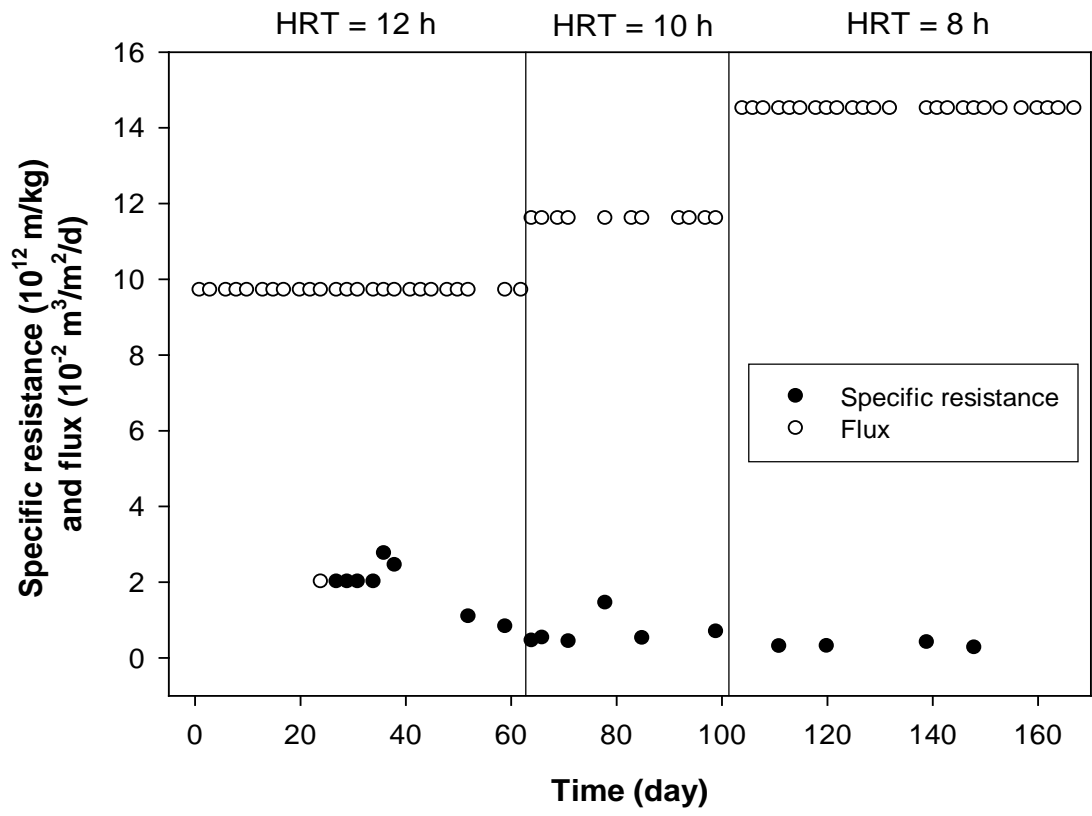


Fig. 5.

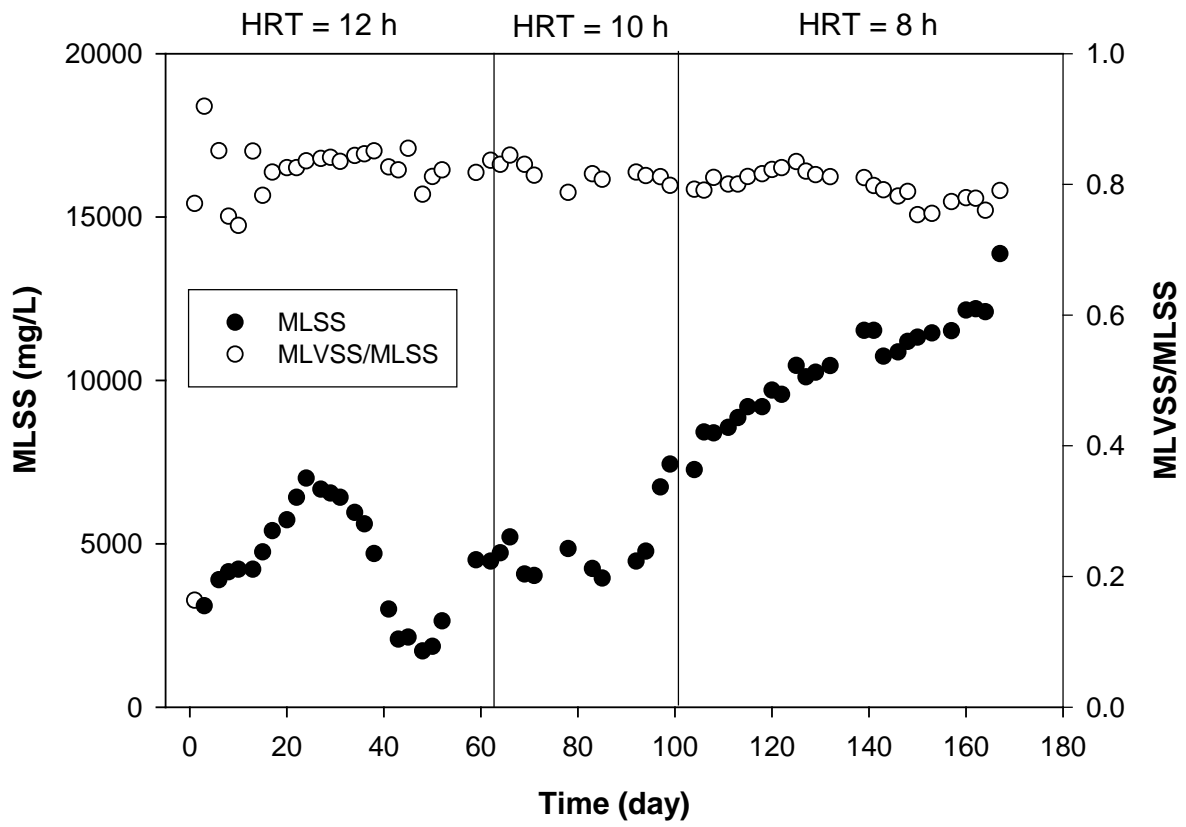


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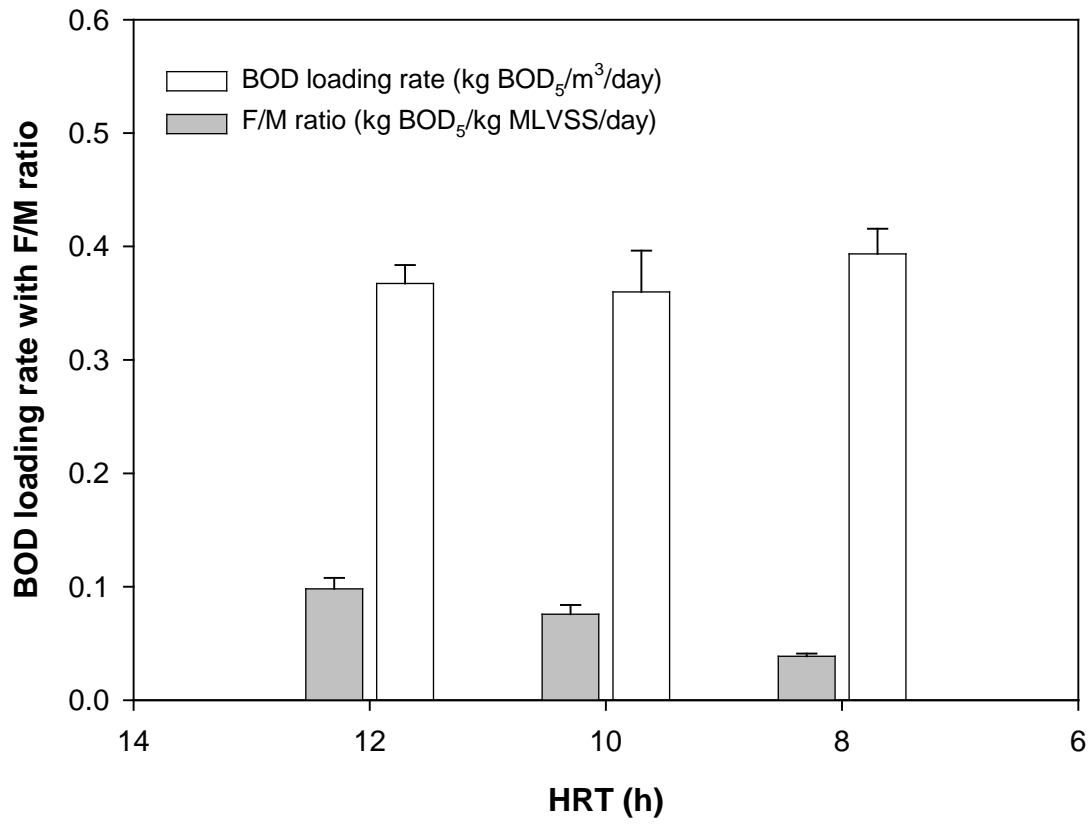


Fig. 7.

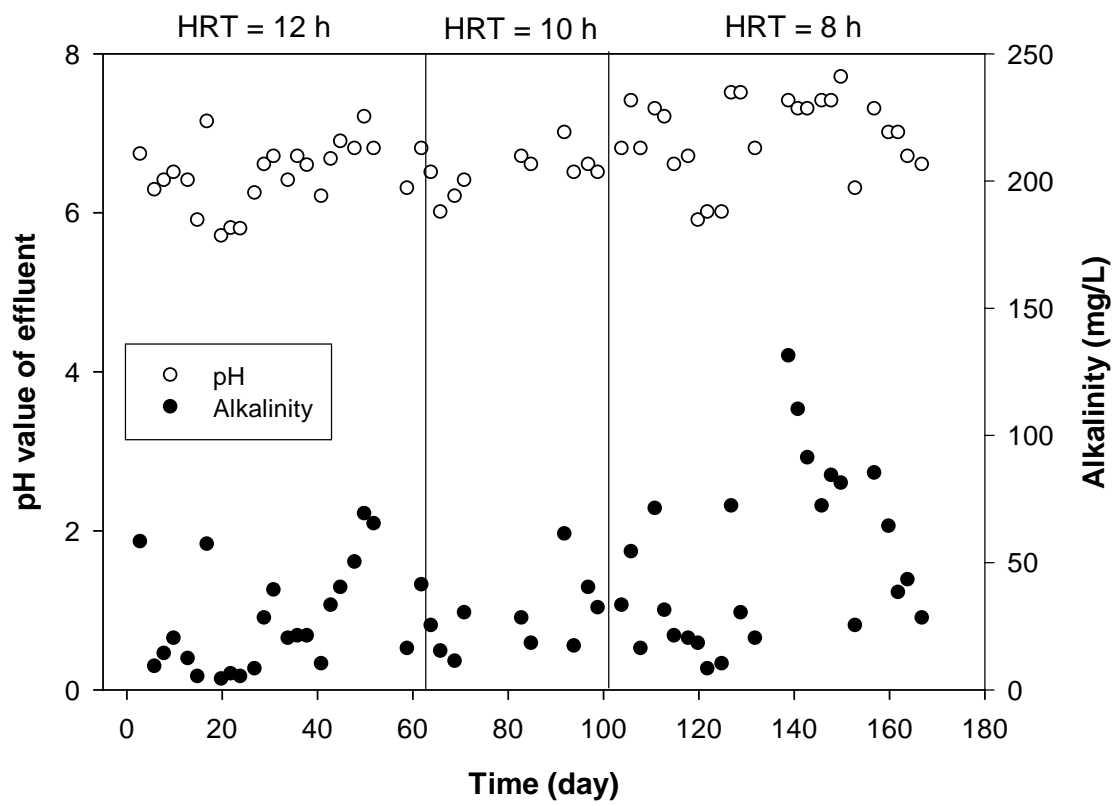


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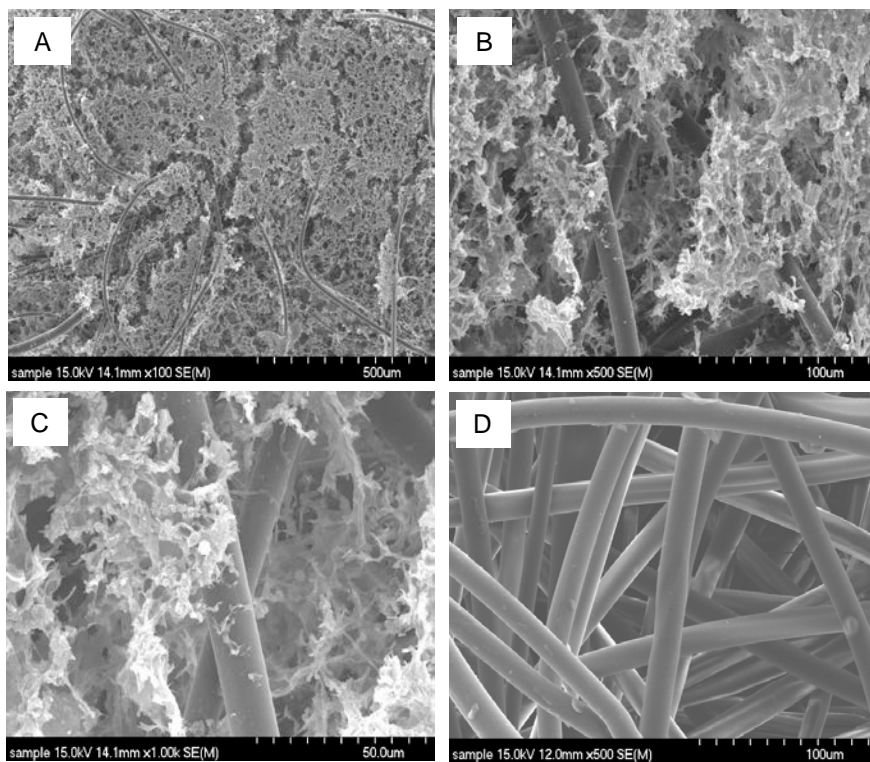


Fig. 9.

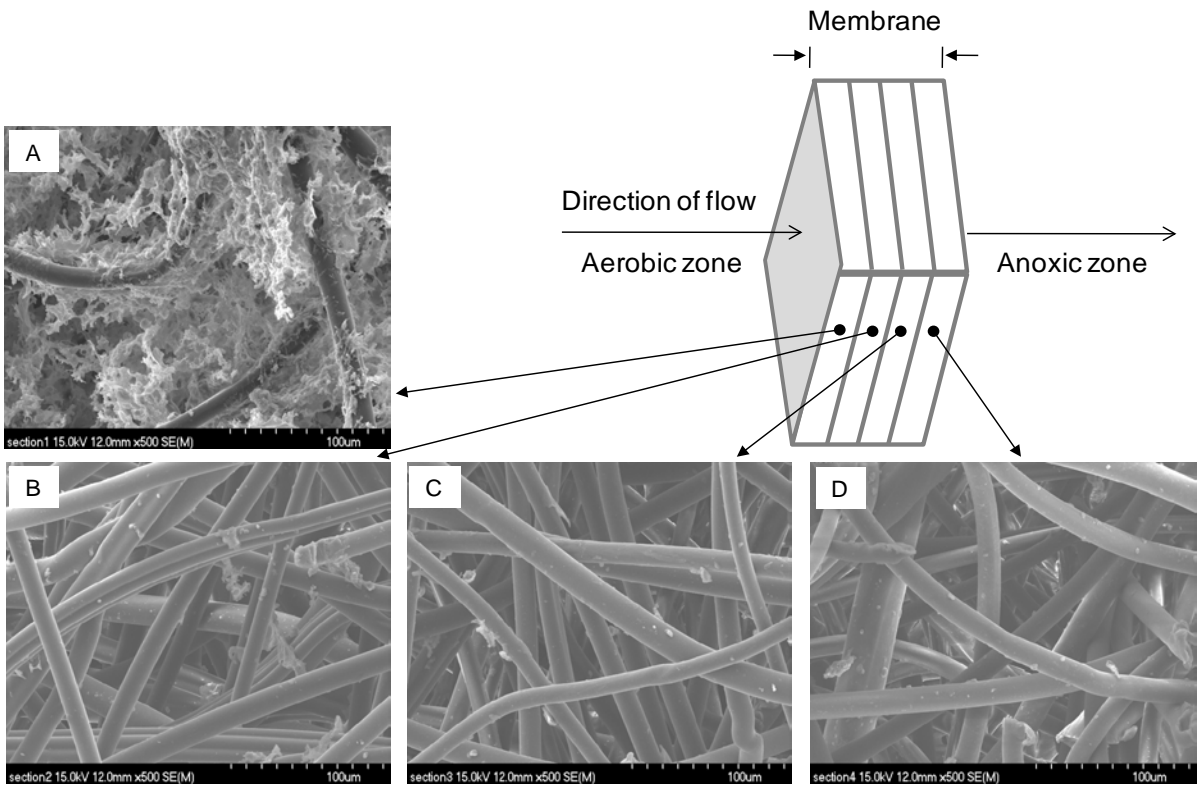


Fig. 10.

