Enhancement of the performance of anaerobic fluidized bed bioreactors (AFBBRs) by a new starch based flocculant

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Abstract

In this study, laboratory-scale anaerobic fluidized bed bioreactors (AFBBRs) using granular activated carbon as bedding material were employed for treating a primary treated sewage effluent (PTSE) with or without refractory organic pollutants (ROPs). A new starch based flocculant (NSBF) combining a nature starch based cationic flocculants and trace nutrients was prepared and applied in AFBBR. The impact of NSBF on the performance of AFBBR was mainly evaluated in terms of organic and nutrient removal and microbial activity. Membrane fouling based on critical flux was assessed when the bioreactor used as pretreatment for microfiltration. The results indicated that the addition of NSBF in AFBBR (NSBF-AFFBR) not only attained improved organic (9-10%) and nutrient removal (10-20%), higher biomass growth (3.0 $g_{biomass}/L_{GAC}$) and net bed expansion (18 cm), but also doubled the critical flux (from 15 to 30 $L/m^3.h$) in the microfiltration system. In addition, NSBF-AFBBR could retain 10% better DOC removal efficiency at different recirculation rates for treating PTSE with ROPs. When increasing organic loading rate from 21.6 to 43.2 kg $COD/m^3 \cdot day$, NSBF-AFBBR achieved comparatively constant organic removal of 55% whereas the efficiency in AFBBR alone decreased dramatically from 47 to 34%. Thus, NSBF could act as a performance enhancer for AFBBR.

Keywords: Anaerobic fluidized bed bioreactor; Bioflocculation; Refractory organic pollutants; Microfiltration; Critical flux

1. Introduction

Continued population growth, contamination of surface water and groundwater and frequent droughts have contributed to inadequate water supplies and water qualities deterioration. Public concerns over health and the environment have led to a need to treat effluents to a higher level. As one of the most hazardous pollutants, refractory organic pollutants (ROPs) such as humic substances in wastewater are generally hard-to-decomposed by microorganisms in secondary treatment process. Even though they usually present a very low concentrations in the wastewater compared to other pollutants, they are very harmful to the human health and environment due to their persistence against chemical/biological degradation [1]. They can react with disinfectants such as chlorine and form trihalomethanes (THMs) and other halogenated by-products as well as organic halides. Many of these halogenated organic compounds are carcinogens or mutagens and are toxic at high concentrations. Thus, the hazardous pollutants including ROPs need to be removed to permissible limits for the safe disposal of wastewater.

Biological wastewater treatment is one of the most cost-effective ways to remove the organic and nutrient contents from wastewaters. In anaerobic treatment processes, anaerobic fluidized bed bioreactor (AFBBR) that utilizes small fluidized media particles to induce extensive cell immobilization has emerged as a good alternative for wastewater treatment with the merits of high surface area available for biomass and substrate, high organic loading rate and short hydraulic retention time over other kinds of anaerobic processes [2, 3]. Maloney et al. [4] have reported that treatment of propellant wastewater by AFBBR was effective in laboratory and field feasibility studies. The AFBBR was able to reduce the concentration of diaminotoluene (DNT) by more than 90% at the high-strength source and could meet discharge permit limitations. Atikovic et al. [5] also investigated the biological degradation of AFBBR which has been shown to be an effective method for removing perchlorate and royal demolition explosive (RDX) in army ammunition production wastewater.

However, the most significant variable in the digestion of FBBR is the selection of support media for microbial adhesion, as anaerobic digestion has a low growth rate of anaerobic bacteria [6]. Depending on previous studies, many supporting media have been used in FBBR such as granular activated carbon (GAC), sand, perlite, zeolite, lava rocks and synthetic resin with considerably successful application [2, 7, 8]. Use of GAC in FBBR is an emerging technology for difficult-to-degrade organics, operated under anaerobic conditions, as it has a strong affinity for attaching organic substances thus offering an ideal environment for enhanced biodegradation. In AFBBR, there are two removal mechanisms occurring simultaneously: (i) the GAC acts primarily as a support media and the adsorbed organics are biodegraded by biofilm attached on GAC and (ii) the adsorptive capacity of the GAC can cut-off peaks of influent concentration through adsorption and later desorbs the contaminants when the bacteria have reduced the aqueous phase concentration, which allows the bacteria to work at a relatively steady state mass removal [9]. Khodadoust et al. [10] evaluated anaerobic GAC-FBBRs for treating wastewater containing pentachlorophenol (PCP). Throughout the various phases of reactor operation, more than 99% PCP and 95% COD were reduced. GAC provided an excellent attachment surface for the biofilm in addition to effectively adsorbing PCP and its biotransformation compounds. In another study, Maloney et al. [9] demonstrated a pilot scale AFBBR containing GAC to treat a pinkwater consists of trinitrotoluene (TNT) and RDX as well as other hazardous by-products. The results showed that TNT and RDX could be effectively treated by anaerobic bacteria under widely varied contaminant concentrations. The system not only lowered the total cost on a yearly basis, but also eliminated the generation of hazardous waste.

Starch is an effective natural polymer for creating reactive cationic moieties using positively charged groups, for instance, amino, imino, ammonium etc. [11]. Although inorganic and organic synthetic polymer flocculants have been superior to starch based flocculants due to their high flocculating efficiency, nonbiodegradable property presents the major drawback of polymeric flocculants, which will lead to secondary pollution for the environment and health impact for human being [12]. Since starch derivatives offer inherent advantages over inorganic and synthetic polymer flocculants such as being derived from a renewable source of raw materials, very low cost, and easily degradable in the environment after use [13], the starch flocculants can cause less ecological problems in the long term than a persistent one while providing carbon source for the microbial activities in biological treatment processes. The previous study found that the natural starch based cationic flocculant could enhance the biomass growth and aggregation process in a fluidized-bed GAC bioreactor [14].

In this study, a new starch based flocculant (NSBF) developed from previous study [15] was applied to AFBBR for improving organic and nutrient removal from a primary treated sewage effluent (PTSE). This modified NSBF was evaluated through both of the AFBBR’s performance and microbial aspects. The main objectives of this study are: i) to investigate the effects of NSBF addition on treating PTSE with and without ROPs in terms of organic and nutrient removal, oxidation-reduction potential (ORP), bed expansion and biomass growth, ii) to evaluate the fouling potential of the effluent from AFBBR to a submerged microfiltration (SMF) system using critical flux as indicator, and iii) to evaluate the performance of AFBBR (with and without NSBF) on removing organics addition under different hydrodynamic conditions.

2. Materials and methods

2.1. Wastewater

Table 1 shows the composition of the synthetic wastewater used in this study. The synthetic wastewater originally contained biodegradable organic pollutants together with some trace nutrients, which was used to simulate PTSE (just after primary treatment process). The ROPs in the PTSE contained natural organic matter such as humic acid, tannic acid, lignin, polysaccharide and other high molecular carbohydrates, which contributed about 10 mg/L dissolved organic matter to PTSE. The synthetic PTSE with and without ROPs has DOC of 110-125 mg/L and 100-115 mg/L respectively.

Table 1
Composition of synthetic PTSE used

2.2. GAC used

The coal based GAC (ACTICARB GS1300, Activated Carbon Technologies Pty Ltd., Australia) was used in this study. This coal based GAC has a surface area of >1100 BETm^2/g, an iodine number of >1100 mg/ (g.min) and maximum ash content of 10%. Prior to use in experiments, the GAC was rinsed with distilled water to remove fines and dried at 105 ºC in the oven.

2.3. New starch based flocculant (NSBF)

The NSBF used in this study was the combination of a nature starch based cationic flocculant and trace nutrients ($CaCl_2$, $MgSO_4$ and $FeCl_3$) which were helpful for biomass growth. The starch based cationic flocculant was provided by HYDRA 2002 Research, Development and Consulting Ltd., Hungary. The major components of this flocculant are cationic starch ether and water. It is completely soluble in water with a density of 1050 kg/m^3.

2.4. AFBBR

In this study, laboratory-scale AFBBRs with 1200 mm long and 25 mm inner diameter were employed. 200 mL of fresh GAC was added in each AFBBR to have an actual (non-fluidized) filter depth of 500 mm. PTSE was pumped through the AFBBRs at the flow rate of 14.4 L/day and organic loading rate of 21.6 $kgCOD/m^3 \cdot d$. Fluidization of GAC with the initial bed expansion of 10 cm was achieved through recycling the effluent from near the top to the bottom assembly at the superficial velocity of 40.76 cm/min. NSBF was continuously added to AFBBRs by dosing pumps with a dosage of 22 mg/L(water treated). Samples of feedings and the effluents from AFBBRs were taken after filtering through 0.45 μm filter prior to analyzing

DOC (Analytikjena Multi N/C 2000 Analyzer) and nutrients (NOVA 60, Merck). The ORP and bed expansion were measured every day and the samples were taken every 5 days for analyzing ammonium nitrogen (NH_4-N), total nitrogen (T-N) and total phosphorus (T-P).

2.5. AFBBR-Submerged microfiltration (SMF) hybrid system

As AFBBR sometimes can be designed as a pretreatment to membrane unit for wastewater treatment, and flocculation is able to remove some large molecular weight refractory organic matter rather than GAC adsorption, in this study, microfiltration was used to test whether NSBF addition could improve membrane performance and reduce fouling. The schematic diagram of the AFBBR-SMF hybrid system is shown in Fig. 1. The effluent from AFBBR was delivered to the membrane reactor by a feeding pump. A hydrophilic polyethylene hollow fiber microfiltration membrane module with pore size of 0.1 μm and surface area of 0.05 m^2 was used. The compressed air was supplied to the membrane reactor with the flow rate of 8 L/min. The permeate flow rate of the membrane was controlled by a suction pump. Flux-step method was applied to determine the critical flux [16]. With the synthetic PTSE or pretreated PTSE, the flux-step experiments were carried out at a step height of 5 L/m^2.h and duration of 60 mins with the initial flux of 10 L/m^2.h. When the filtration period was finished (after 60 mins), the membrane was backwashed with the distilled water at the flux of 30 L/m^2.h for 1 min. After each experiment, the membrane was chemically cleaned.

Fig. 1. Experimental set-up of AFBBR-SMF hybrid system

3. Results and Discussion

3.1. Effects of NSBF addition on PTSE with and without ROPs

3.1.1. Organic and nutrient removal

Two sets of experiments were carried out in parallel and each set consists of two AFBBRs (one fed with PTSE and the other one with PTSE+ROPs). NSBF was added in one set of AFBBRs continuously at the dosing rate of 22 mg/L. Fig. 2 illustrates organic removals at organic loading rate of 21.6 kgCOD/m^3·d for 50 days and all the systems performed stably from the 15th day of operation. For treating PTSE without ROPs, the results indicated that NSBF-AFBBR had 10% better DOC removal rates (61.1±3.6%) than those of AFBBR (51.3±3.2%). Although overall DOC removal efficiencies reduced slightly due to the ROPs presented in PTSE, NSBF-AFBBR again exceeded AFBBR in DOC removal efficiency by 9%, resulting in removal of 57.3±2.9% and 48.2±3.5% respectively. Thus, NSBF addition could improve organic removal ability of AFBBR because NSBF can provide extra carbon source and trace nutrients to promote the microorganism growth. Based on the previous studies, the addition of carbon source and trace nutrients was very necessary for the biomass growth in the AFBBR operation [17, 18]. As microorganism attached on GAC could biodegrade organics adsorbed on the surface of GAC and then release the site for further organics absorbance continuously, most of organic contained in PTSE could be removed from AFBBR, including partial ROPs.

Fig. 2. Performance of AFBBRs and NSBF-AFBBRs for treating PTSE with and without ROPs (initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d, recirculation rate = 95%, influent DOC = 110-125 mg/L (with ROPs) and 100-115 mg/L (without ROPs))

Table 2 summarises the nutrients removal of AFBBRs after 50-day operation. Since the experiments were conducted under anaerobic condition, the NH_4-N, T-N and T-P removals of AFBBR and NSBF-AFBBR for treating PTSE without ROPs were approximately 17% and 37%, 18% and 37%, 18% and 34% respectively. With ROPs, NSBF-AFBBR still could exceed AFBBR in nutrient removal efficiencies by around 10%. The NO_3-N and NO_2-N concentrations of the effluent were less than 0.5 and 0.01 mg/L respectively in all cases.

Table 2
The nutrients removal of AFBBRs with and without NSBF addition (influent NH_4-N = 16-19 mg/L, NO_3-N = 0.6-1.1 mg/L, NO_2-N = 0.01-0.02 mg/L, T-N = 17-20 mg/L, T-P = 2.9-3.2 mg/L)

3.1.2. Oxidation-reduction potential (ORP) of AFBBRs

During the experiments, pH values of the feeding wastewaters were always kept at 7 and no further pH adjustment was employed for AFBBRs. The pH values for AFBBRs were dropped to 4.7-5.0 at the beginning of operation. After that, the pH values increased gradually and reached steady phases around 20th day which meant the microbial reactions of anaerobic microorganism [19]. The AFBBRs without NSBF addition had consistent pH values of 6.1 (PTSE only) and 6.4 (PTSE+ROPs) respectively, while the opposite ones obtained higher pH readings (6.8 for PTSE and 6.7 for PTSE+ROPs). To give a further explanation, Fig. 3 illustrates the ORP variations of the GAC beds in AFBBRs and NSBF-AFBBRs. It can be seen that ORPs of the GAC bed in NSBF-AFBBR dropped sharply from 210 to -416 mV within 15 days and remained at around -410 mV for the rest of operation when treating synthetic PTSE without ROPs existence. With the same feed, the ORPs in AFBBR dropped comparatively slow and took 41 days to stabilize at approximately -342 mV. The data also show that anaerobic condition established in NSBF-AFBBR (ORP< -100 mV, according to Dabkowski [20]) on the 11th day which was 8 days earlier than the counterpart. Similarly, with the presence of ROPs in synthetic PTSE, the AFBBR and NSBF-AFBBR reached anaerobic conditions on 12th day and 15th day, respectively, and NSBF-AFBBR always maintained lower ORPs. The faster decrease of ORP in the NSBF-AFBBRs indicated NSBF could enhance the activity of anaerobic microorganism attached on GAC by providing extra nutrients and carbon source for heterotrophic bacteria growth, resulting in less pH reductions.

Fig. 3. ORP variations of the GAC beds in AFBBRs and NSBF-AFBBRs for treating PTSE with and without ROPs (initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d, recirculation rate = 95%)

3.1.3. Bed expansion and biomass growth

The bed expansion of AFBBRs under different conditions is shown in Fig. 4. The initial GAC bed expansion and superficial velocity were 10 cm and 40.76 cm/min, respectively. With the growth of the biomass, bed expansion kept increasing for the first 14 days and then achieved steady phase afterwards. It is observed that the GAC bed expansion increased from 10 cm to 22.5 cm in NSBF-AFBBR when ROPs were not present, while only 2.5 cm net bed expansion gained for AFBBR (Fig. 4 (a)). With the additional ROPs to the synthetic PTSE, the similar results were observed (18.5 cm in NSBF-AFBBR and 12 cm in AFBBR). Fig. 5 shows the relations between biomass growth on GAC and net bed expansion. The biomass concentration of GAC is defined as biomass per unit volume of GAC. A certain volume of GAC particles were taken from near the top of the NSBF-AFBBR (feeding with PTSE+ROPs) bed and were shaken using distilled water until all the biomass attached on the GAC particles sloughed off. The biomass was measured by APHA Standard Method [21]. The trend line elucidates that expansion values are directly proportional to the biomass growth (with R^2=0.9851). The data also demonstrated that the net bed expansion increased dramatically from 12.5 cm to 18 cm when attached biomass increased from 2.2 to 3.0 $g_{biomass}/L_{GAC}$. Therefore, the more biomass attached on GAC could lead to the higher bed expansion in AFBBR. Since the bed expansion of NSBF-AFBBRs was much higher than that of AFBBRs, it suggested that NSBF could successfully support anaerobic microbial growth on GAC as well as aggregate particles in AFBBRs.

Fig. 4. Bed expansion of AFBBRs and NSBF-AFBBRs for treating (a) PTSE without ROPs; (b) PTSE with ROPs (initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d, recirculation rate = 95%)

Fig. 5. The relations between biomass growth on GAC and net bed expansion (initial GAC depth = 50 cm)

As the bed expansion of the AFBBR depends on the physical characteristics of the liquid phase, the superficial velocity and the biomass attached on GAC, after 50 days operation, the bed expansion was measured at the different superficial velocities using fresh GAC, the inoculated biological GAC (BGAC) from AFBBR and

NSBF-AFBBR feeding with PTSE with ROPs (initial GAC bed depth 50 cm). The minimum fluidization velocities of fresh GAC, BGAC of AFBBR and BGAC of NSBF-AFBBR were found to be 24.46, 20.38 and 14.26 cm/min, respectively. Fig. 6 demonstrates that net bed expansion is almost proportional to superficial velocity for these three different GACs. Both of BGACs from AFBBR obtained the higher bed expansion than that of fresh GAC, and BGAC of NSBF-AFBBR achieved the highest bed expansion when comparisons were made at the same superficial velocity. According to Grady et al. [22], the growth of the biomass on the medium enlarges the particles diameter and also decreases the density of particles. Rovatti et al. [23] also reported the biofilm coated sand was easier to fluidize than the fresh sand in the AFBBR. Therefore, BGAC exhibited higher bed expansion than fresh GAC even at the same superficial velocity. Besides, NSBF was proved again that it could indeed stimulate microbial growth of AFBBRs.

Fig. 6. Net bed expansion of three different GACs (initial GAC depth = 50 cm)

The detailed scanning electron microscope (SEM) images of the fresh GAC (a), GAC from AFBBR (b) and GAC from NSBF-AFBBR (c) clearly display the surface of GAC particle before and after the colonization of microorganism (Fig. 7). The great superficial porosity of fresh GAC is obvious in image (a) and is a characteristic that brings high specific surface area. For image (b) with a lower biomass concentration there is an accumulation of microorganisms together with partially visible crevices, whereas the surface of particle (c) is fully covered and biomass is distributed more evenly.

Fig. 7. SEM images of (a) fresh GAC; (b) GAC from AFBBR; and (c) GAC from NSBF-AFBBR

3.2. Performance of AFBBRs as pretreatment to submerged microfiltration (SMF) hybrid system

The performance of AFBBRs and NSBF-AFBBRs as pretreatment to SMF was evaluated in terms of critical flux. Fig. 8 depicts the critical fluxes under different feeding conditions: (a) PTSE with ROPs, (b) effluent from AFBBR, and (c) effluent from NSBF-AFBBR. The results show that the AFBBRs as pretreatment could improve the permeability of membrane. Compared with the critical flux of wastewater alone (15 L/m^{2}·h), the effluent pretreated by AFBBR increased the critical flux up to 25 L/m^{2}·h and the addition of NSBF into AFBBR could help in achieving highest critical flux up to 30 L/m^{2}·h.

Fig. 8. Constant filtration fluxes vs. TMP of SMF under different feeding conditions (a) PTSE with ROPs; (b) effluent from AFBBR; and (c) effluent from NSBF-AFBBR

Accordingly, for PTSE without ROPs, the TMP appeared constant for the filtration flux up to 20 L/m^{2}.h while it began to increase at higher filtration flux due to membrane fouling. The critical flux was found to be 25 and 30 L/m^{2}.h for the effluents from AFBBR and NSBF-AFBBR, respectively. Hence, the AFBBRs as pretreatment to SMF could reduce the organic loading to membrane to some extent, resulting in a decrease in membrane fouling and an increase in membrane permeability.

3.3. Effect of recirculation rate and organic loading rate (OLR)

The effects of different operational conditions (such as recirculation rate and OLR) on removing organics from NSBF-AFBBR and AFBBR were evaluated to treat PTSE with ROPs. Fig. 9 shows the performance of NSBF-AFBBR and AFBBR in removing DOC from wastewater at different recirculation rate which descended from initial 95% to 90% and then 80%. As can be seen from the figure, the decrease in recirculation rate led to reduced DOC removal efficiency for both systems. With the highest recirculation rate (95%) applied, the best removal efficiencies (57.5±1.2% for NSBF-AFBBR and 47.4±1.5% for AFBBR) were achieved. Corresponding to reduced recirculation rate from 90% to 80%, the DOC removal efficiencies of NSBF-AFBBR and AFBBR dropped from 51.1±1.3% to 46.8±2.0% and 41.4±1.5% to 36.3±1.8%, respectively. Thus, the higher recirculation rate favors higher organic removal. Similarly, Koran et al. [24] reported an anaerobic GAC-FBBR was highly effective to remove recalcitrant organics from a synthetic waste stream by recirculating of the effluent at an approximate recycle ratio of 200:1. As NSBF-AFBBR always maintained 10% better removal efficiency than AFBBR, which indicated that changing the recirculation rate did not affect the performance of NSBF.

Fig. 9. Performance of AFBBR and NSBF-AFBBR in removing DOC at different recirculation rate (wastewater: PTSE+ROPs, influent DOC = 110-125 mg/L, initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d)

The OLRs of NSBF-AFBBR and AFBBR were increased from 21.6 to 54 kgCOD/m^3·d in four steps. Each organic loading rate was operated for 15 days to investigate the possible adaptation of anaerobic bacteria to these loading rates. As shown in Fig. 10, it was evident that AFBBR was unable to provide stable DOC removal and the gap between two systems was obviously enlarged from OLR of 32.4 kgCOD/m^3·d. The DOC removal efficiency dropped sharply from 47.0±1.4% (21.6 kgCOD/m^3·d) to 36.9±2.4% (32.4 kgCOD/m^3·d) and then to 33.7±1.4% (43.2 kgCOD/m^3·d). On the contrary, with a slight decrease of DOC removal, NSBF-AFBBR presented much better stability (55.3±1.0% removal) to the variation in OLR up to 43.2 kgCOD/m^3·d. This again demonstrated the important role of NSBF that it can assist the AFBBR system in responding favorably to the organic shocking load. However, the present results revealed the existence of an organic loading rate threshold for both of AFBBRs. At 54 kgCOD/m^3·d OLR, only 35.5±0.9% of organic pollutants could be eliminated from NSBF-AFBBR even though it had 15% higher efficiency superior to AFBBR.

Fig. 10. Performance of AFBBR and NSBF-AFBBR in removing DOC at different OLR (wastewater: PTSE+ROPs, initial GAC depth = 50 cm, initial bed expansion = 10 cm, recirculation rate = 95%)

4. Conclusions

The study applied a new starch based flocculant to AFBBR and its impact on the performance was investigated. The results of this study showed the successful use of NSBF as a system performance enhancer. With NSBF addition the AFBBRs resulted in better removal efficiency and microbial activity than conventional AFBBRs when treating synthetic PTSE (with or without ROPs). The findings draw the following conclusions:

- Addition of NSBF to the AFBBR was helpful for biomass growth on GAC and enhanced the performance of AFBBR in terms of organic and nutrient removal.

- NSBF was favorable for the activity of anaerobic microorganism attached on GAC.
- NSBF-AFBBR as pretreatment to SMF was successful in reducing membrane fouling and increasing the critical flux up to 30 L/m^2.h.
- NSBF-AFBBR always performed better than AFBBR by approximately 10% in organic removal with varied recirculation rate.
- With ROPs presented in PTSE, NSBF-AFBBR endured high OLR with stable organic removal rate up to 43.2 kgCOD/m$^3\cdot$d while AFBBR was sensitive to organic shocking load and showed deteriorated result.

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Table 1

Composition of synthetic PTSE used

Compound	Concentration (mg/L)
Glucose	230
$(NH_4)_2SO_4$	71
KH_2PO_4	13.2
Trace nutrients	
$MgSO_4.7H_2O$	5.07
$CaCl_2.2H_2O$	0.368
$MnCl_2$.4H2O	0.275
$ZnSO_4.7H_2O$	0.44
$FeCl_3$	1.45
$CuSO_4.5H_2O$	0.391
$CoCl_2.6H_2O$	0.42
$Na_2MoO_4.2H_2O$	1.26
Yeast extract	20
Refractory organic pollutants	
Humic acid	4.2
Tannic acid	4.2
(Sodium) lignin sulfonate	2.4
Sodium lauryle sulphate	0.94
Acacia gum powder	4.7
Arabic acid (polysaccharide)	5

Table 2

The nutrients removal of AFBBRs with and without NSBF addition (influent NH_4-N = 16-19 mg/L, NO_3-N = 0.6-1.1 mg/L, NO_2-N = 0.01-0.02 mg/L, T-N = 17-20 mg/L, T-P = 2.9-3.2 mg/L)

Wastewater	NH_4-N removal efficiency (%)		T-N removal efficiency (%)		T-P removal Efficiency (%)	
	with NSBF	without NSBF	with NSBF	without NSBF	with NSBF	without NSBF
PTSE	37.0±2.3	17.2±2.7	36.8±2.1	18.1±2.5	33.5±1.3	18.1±3.1
PTSE+ROPs	31.3±2.7	21.5±3.3	32.2±2.7	22.7±3.3	34.3±2.2	23.4±3.5

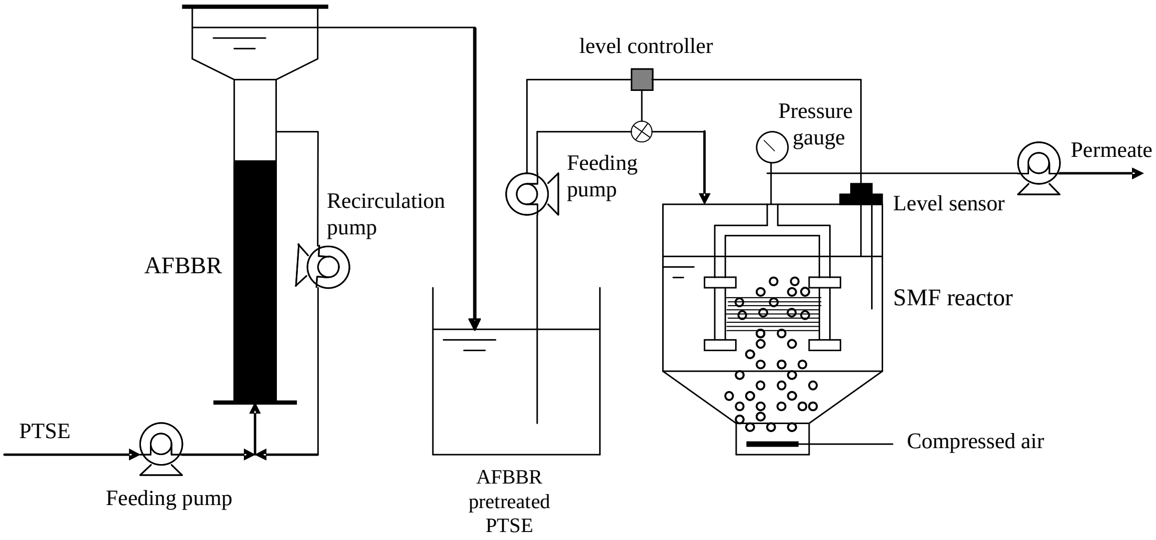


Fig. 1. Experimental set-up of AFBBR-SMF hybrid system

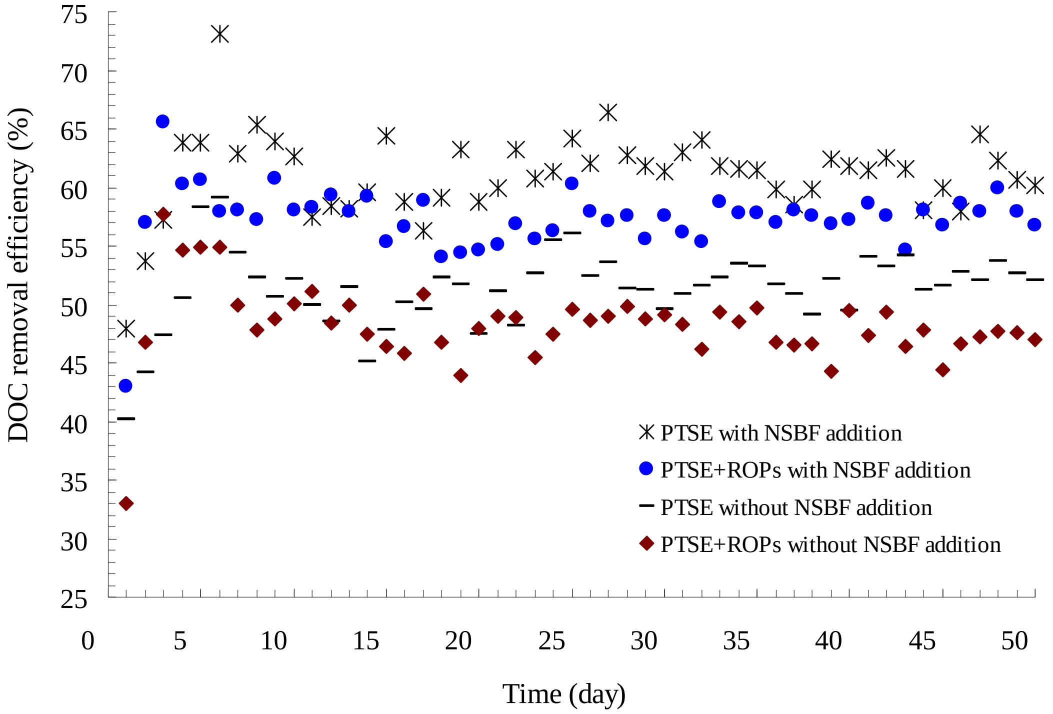


Fig. 2. Performance of AFBBRs and NSBF-AFBBRs for treating PTSE with and without ROPs (initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d, recirculation rate = 95%, influent DOC = 110-125 mg/L (with ROPs) and 100-115 mg/L (without ROPs))

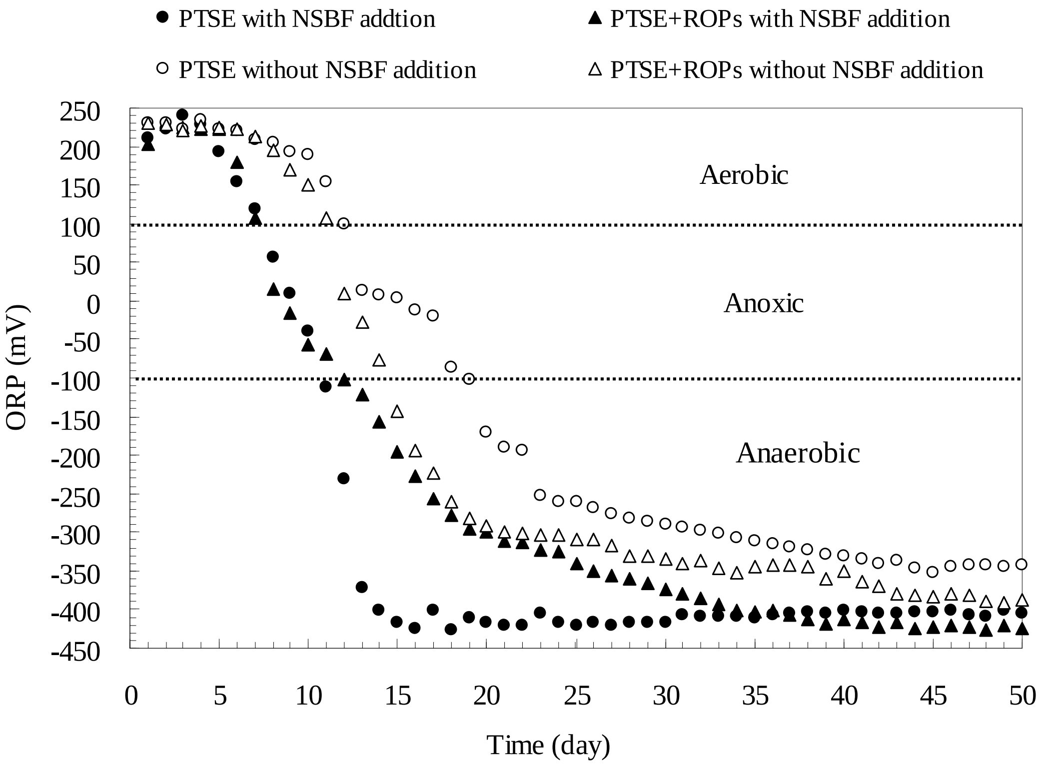
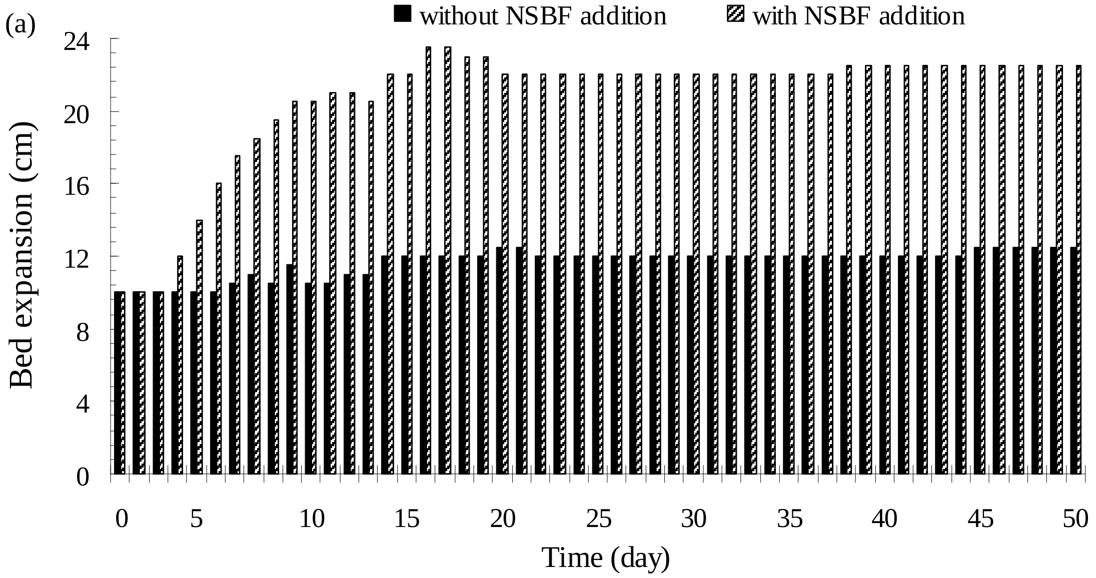


Fig. 3. ORP variations of the GAC beds in AFBBRs and NSBF-AFBBRs for treating PTSE with and without ROPs (initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d, recirculation rate = 95%)


(a)
without NSBF addition
with NSBF addition
Bed expansion (cm)
0
4
8
12
16
20
24
0
5
10
15
20
25
30
35
40
45
50
Time (day)

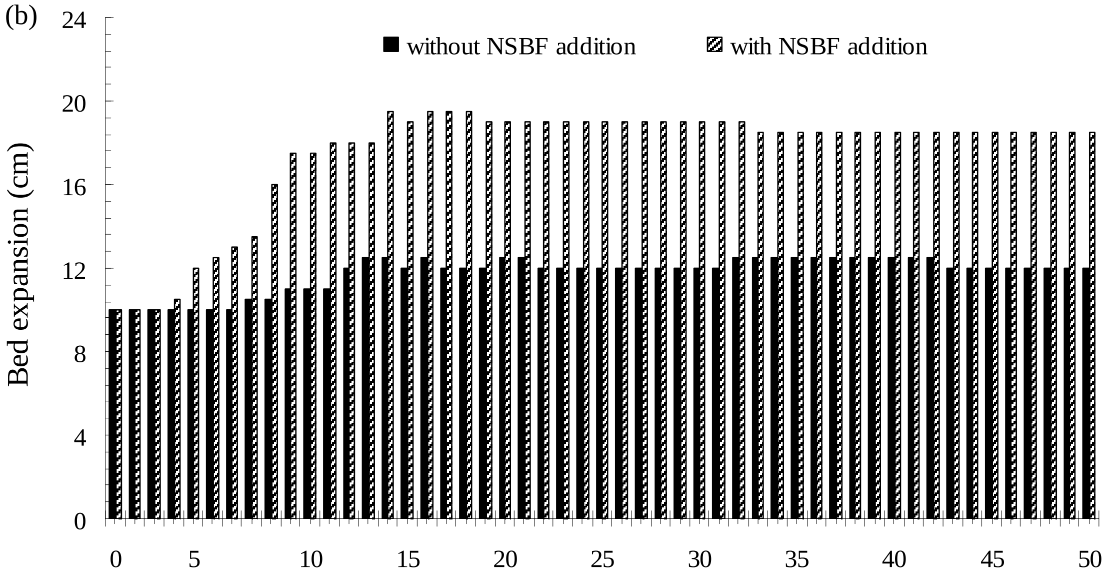

(b)
without NSBF addition
with NSBF addition
Bed expansion (cm)
0
4
8
12
16
20
24
0
5
10
15
20
25
30
35
40
45
50

Fig. 4. Bed expansion of AFBBRs and NSBF-AFBBRs for treating (a) PTSE without ROPs; (b) PTSE with ROPs (initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d, recirculation rate = 95%)

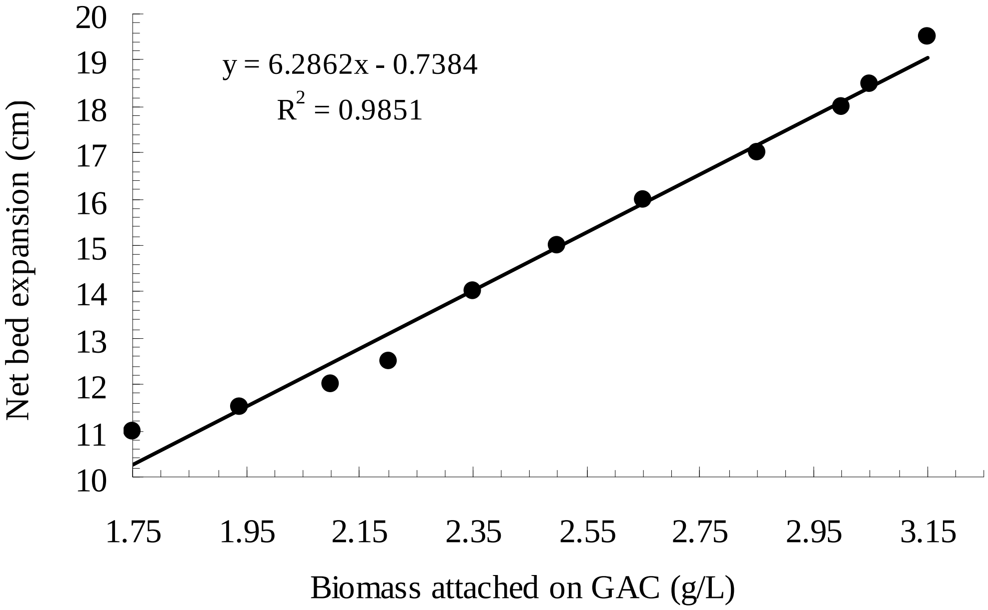


Fig. 5. The relations between biomass growth on GAC and net bed expansion (initial GAC depth

= 50 cm)

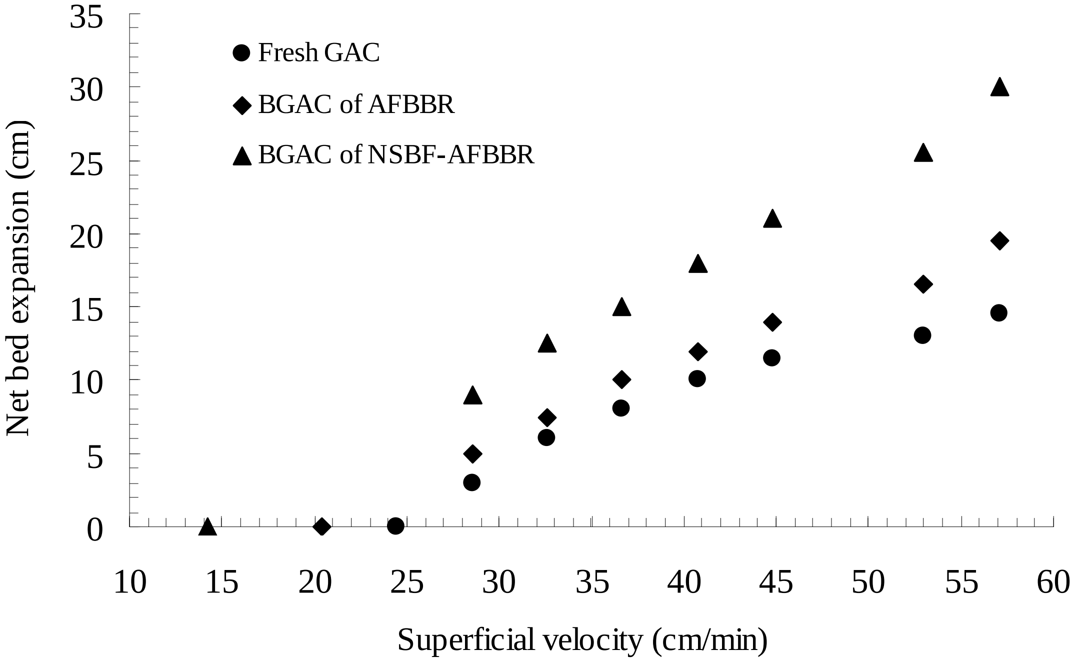
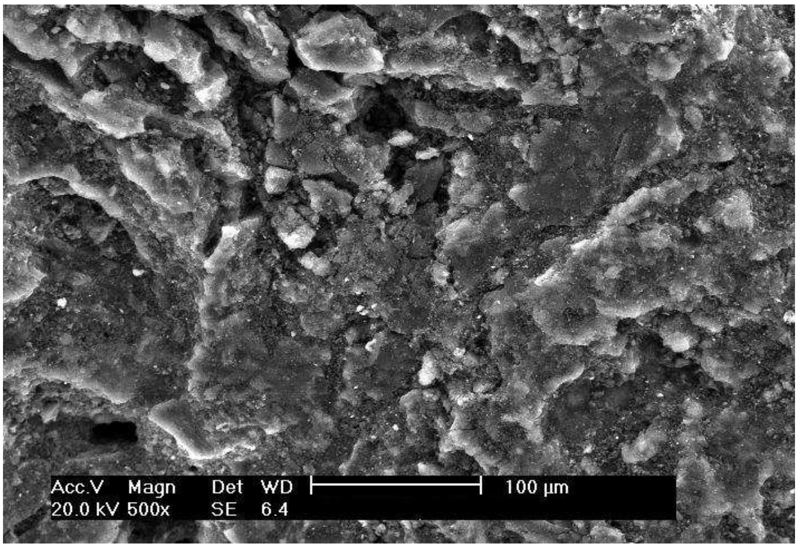

Net bed expansion (cm)
0
5
10
15
20
25
30
35
Superficial velocity (cm/min)
10
15
20
25
30
35
40
45
50
55
60
● Fresh GAC
◆ BGAC of AFBBR
▲ BGAC of NSBF-AFBBR

Fig. 6. Net bed expansion of three different GACs (initial GAC depth = 50 cm)

(a)



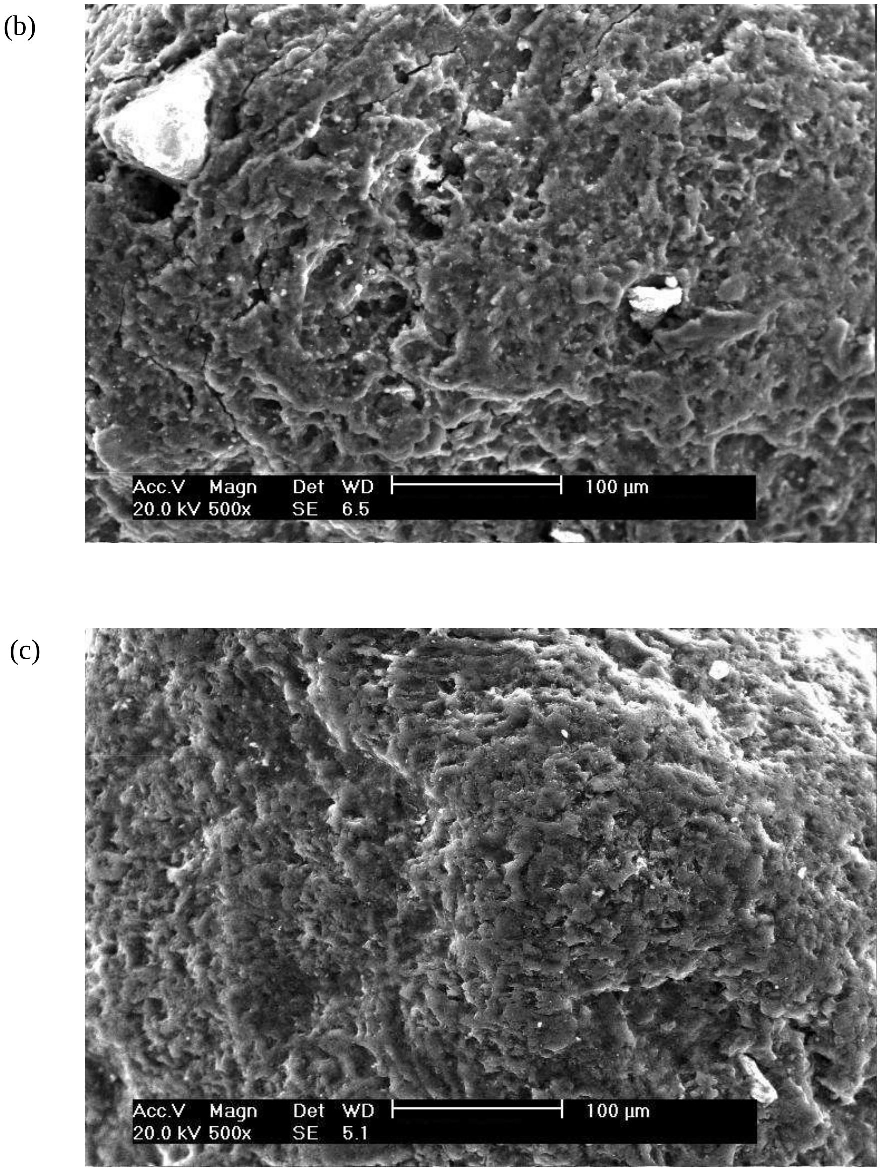


Fig. 7. SEM images of (a) fresh GAC; (b) GAC from AFBBR; and (c) GAC from NSBF-AFBBR

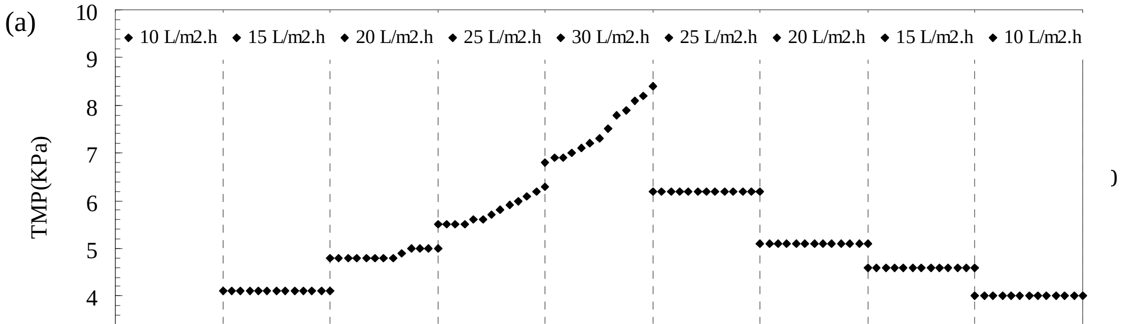


Fig. 8. Constant filtration fluxes vs. TMP of SMF under different feeding conditions (a) PTSE with ROPs; (b) effluent from AFBBR; and (c) effluent from NSBF-AFBBR

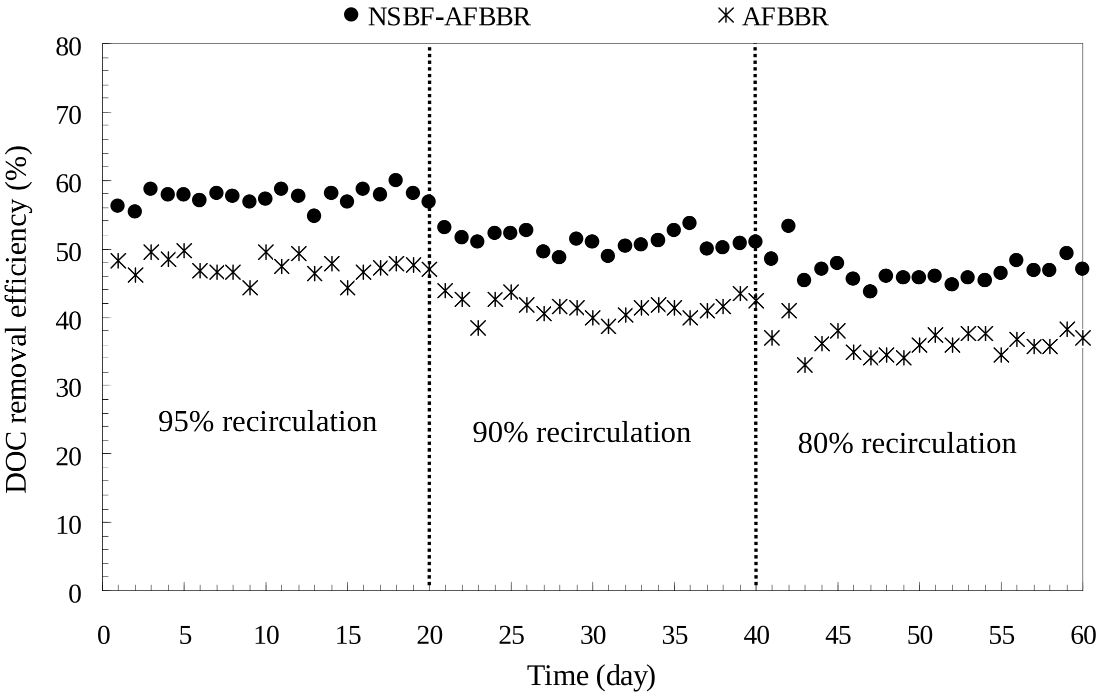


Fig. 9. Performance of AFBBR and NSBF-AFBBR in removing DOC at different recirculation rate (wastewater: PTSE+ROPs; influent DOC = 110-125 mg/L; initial GAC depth = 50 cm, initial bed expansion = 10 cm, OLR = 21.6 kgCOD/m^3·d)

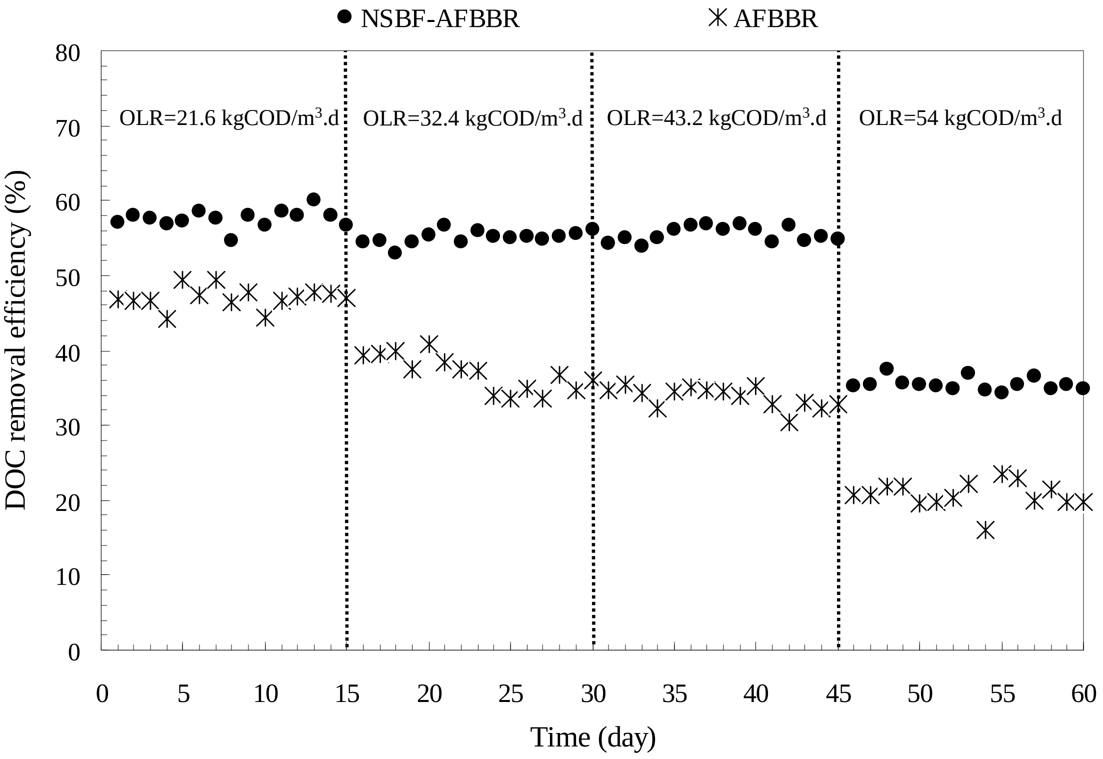


Fig. 10. Performance of AFBBR and NSBF-AFBBR in removing DOC at different OLR (wastewater: PTSE+ROPs; influent DOC = 110-125 mg/L; initial GAC depth = 50 cm, initial bed expansion = 10 cm, recirculation rate = 95%)