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Removal characteristics of organics and nitrogen in a novel four-stage biofilm integrated system for enhanced treatment of coking wastewater under different HRTs

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Abstract

Coking wastewater contains substantial organics and nitrogen, posing a great threat on water environment. In this work, organics and nitrogen removal characteristics within each single reactor of a pilot-scale four-stage biofilm anaerobic/anoxic/oxic/oxic (FB-A^2/O^2) coking wastewater treatment system were specifically investigated at various hydraulic retention times (HRTs). The long-term experiment showed chemical oxygen demand (COD) was greatly degraded in Reactors A_2 and O_1, while ammonia-nitrogen (NH_4^+-N) was mostly removed in Reactor O_2. 116 h was considered to be optimum for treating coking wastewater, achieving the total COD and NH_4^+-N removal efficiencies of 92.3 % and 97.8 %, respectively. Experimental data presented good linear correlations between volumetric loading and removed loading rates among 0.15~0.65 kgCOD/m^3·d and

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0.03~0.07 kgNH_4^+-N /m^3·d, much lower than treating other kinds of wastewater due to its complex composition and high toxicity. HRT also strongly influenced removal characteristics and process performance of each biofilm bioreactor. Vertical spatial distributions in DO, COD, NH_4^+-N and NO_3^--N concentration profiles along the reactor height were obviously observed in the upflow biofilm bioreactor filled with granular media, facilitating the enhancements of organics removal, nitrification and denitrification. The FB-A^2/O^2 system integrating with hydrolysis-acidification, denitrification, carbonization and nitrification identified by dominant bacterial populations in each single reactor was proved to be feasible and efficient to treat poor-degraded and high-toxic coking wastewater.

Keywords: coking wastewater; four-stage biofilm anaerobic/anoxic/oxic/oxic (FB-A^2/O^2); hydraulic retention time (HRT); removal characteristics; bacterial composition

Introduction

Coking wastewater, one of the most toxic and complex industrial effluent from iron and steel production facilities, originates from the process of destructive distillation of coal at high temperatures (900-1100 °C) in the absence of air.[1] Its composition varies depending on the types of raw coal, process modifications and operating conditions in the coke ovens.[2, 3] In China, for example, typical influent coking wastewater generally contains 200-300mg/L biochemical oxygen demand (BOD_5), 1000-2000 mg/L chemical oxygen demand (COD), 200-400 mg/L suspended solids (SS), 200-400 mg/L ammonia-nitrogen (NH_4^+-N), 250-350 mg/L phenols and 5-20 mg/L cyanide as well as large amounts of highly toxic substances involving mono- and polycyclic aromatics hydrocarbons (PAHs) and heterocyclic aromatic hydrocarbons containing nitrogen, oxygen and sulfur.[4-6] Therefore, proper disposal of coking wastewater has become a highly severe issue to be solved urgently for coking industries not only in China but also other countries.

Compared with physico-chemical processes, biological treatments as high-efficient, cost-effective and environment-friendly technologies have been widely applied to treat various domestic and industrial wastewaters. Since the 1970s, quite a wide range of bio-systems have been developed for treating coking wastewater involving conventional activated sludge (CAS) ,[1, 7] fixed biofilm ,[8-10] biological nitrogen removal (BNR) process, [1, 3, 6, 11-13] sequencing batch reactor (SBR), [2, 14, 15] fluidized-bed reactor (FBR) [16-18] and membrane bioreactor (MBR).[19, 20] Unfortunately, most of biological processes were insufficient to successfully remove organic matters and ammonia-nitrogen, leading to the biologically treated effluent greatly exceeding the first-grade discharge standard for coking wastewater in China (COD≤100 mg/L and NH_4^+-N≤15 mg/L), despite quite high removal efficiencies of BOD_5, phenols and cyanide were achieved.

Actually, there are strongly inhibitory effects on both heterotrophic and autotrophic bacteria in aerobic CAS processes for treating coking wastewater due to its complicated composition and high toxicity,[3, 5] resulting in some undesirable problems such as low process efficiency,[1, 2, 7] poor sludge settle-ability [21, 22] and unstable system performance.[23, 24] During recent several decades, attached biofilm systems have been demonstrated as one of the most effective and competitive alternatives for the treatment of high-strength hazardous coking wastewater [5, 11, 13, 25] based on their high volumetric loading rate, high microbial biomass and long mean cell retention time (MCRT) for effective nitrification efficiency and stable effluent quality. It has been also proved that anaerobic process as the pre-treatment can effectively promote the biodegradability and reduce the toxicity of refractory organics in coking wastewater.[25-28] The utilization of anoxic reactor is capable of not only removing total nitrogen, but also enhancing the degradation of refractory organic matters through denitrification at the presence of oxidized nitrogen.[29] In terms of NH_4^+-N removal, enough autotrophic nitrifying bacteria can be easily enriched in two-step aerobic biofilm reactors with very long MCRT, which organic matters are removed in the first aerobic reactor and nitrification is significantly performed in the second aerobic reactor under lower organic loading and toxicity.[30]

Based on the above, a novel four-stage biofilm anaerobic/anoxic/oxic/oxic (FB-A^2/O^2) system, within which hydrolysis-acidification, denitrification, carbon oxidation and nitrification were integrated, was developed to enhance simultaneous carbon and nitrogen removal from high-strength coking wastewater to meet increasingly more stringent discharge standard in China.[31] In the present study, specific removal characteristics of each biofilm bioreactor of the FB-A^2/O^2 system were investigated at various hydraulic retention times (HRTs). Additionally, bacterial compositions linked with bioreactor performance at optimum HRT were also identified by pure culture and microbial analysis.

Materials and methods

Experimental setup

Fig. 1 depicts a pilot-scale integrated coking wastewater treatment system operated for over two years consisting of four up-flow fixed biofilm bioreactors: anaerobic (A_1)-anoxic

(A_2)-oxic (O_1) and oxic (O_2) located at a coking plant of Tongshida Co.Ltd in Linfen, Shanxi Province. The working volumes of four reactors were respectively 3.0 m^3, 4.8 m^3, 4.8 m^3 and 4.8 m^3. Sampling ports were evenly installed at different heights of the packing layer in Reactors A_1, A_2 and O_2. Reactors A_1, A_2 and O_2 were packed with ceramsite to maintain high biomass and develop vertical microbial distribution and fine filtration along the reactor height, while Reactor O_1 was filled with hollow plastic balls to enhance mass transfer efficiency and capable of largely removing COD at high organic loading via filamentous bacteria. The specification of the used bio-packings is listed in Table 1.

Start-up of the system

The seed sludges for anaerobic/anoxic reactors and two-stage aerobic reactors of the whole system were, respectively, obtained from the anoxic tank and aerobic aeration tank of a coke-plant wastewater treatment facility of Tongshida Co.Ltd in Linfen. The raw coking wastewater via pre-treatments (ammonia stripping, oil isolating and air floatation) was collected in the wastewater tank. The characteristics of the influent wastewater are given in Table 2. In the beginning, to relieve high toxicity of coking wastewater, about 0.04 m^3/d raw wastewater diluted with 200 % tap water continuously flowed into the system operated at 28-30°C. Dissolved oxygen (DO) concentration was kept above 4 mg/L in the aerobic reactors using a lower gas-liquid ratio to avoid the washing out of young biofilm during biofilm growth. K_2HPO_4 (C：N：P=100：5：1) was added into the influent tank each day to provide sufficient nutrient elements for the normal growth of microorganisms. After about 2-week period acclimation operated in continuous-flow, with increased influent loading based on continuous a small increase of the flow rate, 0.2 m^3/d of coking wastewater with 50 % tap water was flowed into the system for the stability establishment of the biofilm reactors during biofilm growth. After 32 d, the removal efficiencies for COD and NH_4^+-N of the system without dilution were achieved above 70 % and 65 %, respectively, indicating the microorganisms were successfully acclimated.

Operational conditions

Allowing for HRT considered as one of the most import process parameters to be optimized during coking wastewater treatment,[12, 32] the system continuously operated for 267 days after its successful start-up was investigated under long-term steady-state operational stages (Runs 1-5) shown in Table 3. Throughout the experimental period, the temperature was in the range of 25–35 ℃, pH and alkalinity were controlled through the addition of $NaHCO_3$ solution into the second aerobic reactor so as to compensate the loss of alkalinity due to nitrification. The final effluent pH was maintained above 7.0 and the alkalinity was not be less than 80 mg/L (as $CaCO_3$). DO concentrations in the aerobic reactors supplied by the compressor were kept around between 3.5–5 mg/L and nitrifying recirculation ratio from Reactor O_2 to Reactor A_2 was controlled at 3.0 based on the optimization of internal nitrate recycling in the previous lab-scale study. Only twice back washings of biological filters (Reactors A_2 and O_2) were conducted to wash out intercepted solids substances and aging biofilms for avoiding media clogging during the experiment.

Microbial analysis

Sample collection and handling

A certain amount of bio-packings (ceramic particles from Reactors A_1, A_2 and O_2 and polypropylene polyhedral hollow ball from Reactor O_1) were collected and mixed in the laboratory glass bottles at 4 °C and then immediately eluted with 50 mL of 0.85 % normal saline. And the eluent was diluted with 300 mL of sterile water.

Culture medium

Culture mediums for facultative anaerobic, aerobic heterotrophic and nitrifying bacteria were specifically listed in Table 4.

Isolation and purification

The qualitative analysis for dominant microbial populations within four biofilm reactors at the optimum operational run was undertaken by bacterial isolation and pure culture. 10 mL eluents at different diluted multiples were inoculated into a 500 mL triangle bottle containing 100 mL liquid medium and incubated for 2 d (facultative anaerobic and aerobic bacteria) and 35 d (aerobic nitrifying bacteria) in a rotatory shaker at 30°C, 150 r/min. After that, 0.1 mL culture solution was coated on the plate at 30℃ incubator for 2 d (facultative anaerobic and aerobic bacteria) and 6 d (aerobic nitrifying bacteria) to develop the colonies. The more colonies and faster growing strains were scribed and purified on the plate and then continuously operated for 3-5 times, respectively.

Identification of strains

The morphological, physiological, biochemical characteristics of the strains were identified according to the Bergey's Manual of Determinative Systematic Bacteriology.[33]

Analytical methods

Temperature, pH, DO and alkalinity were measured daily. COD, NH_4^+-N, NO_3^--N were analyzed weekly. Temperature and pH were measured with a pH meter (WTW Multi340i). The DO was measured using a portable DO meter (YSI-500). COD, NH_4^+-N, NO_3^--N and alkalinity both in the influent and effluent of each single bioreactor were analyzed according to Standard Methods.[34]

Results and discussion

Overall removal efficiency

Figure 2 depicts the average COD and NH_4^+-N concentrations from the influent to effluent and corresponding removal efficiencies at different HRTs. It was clearly demonstrated that COD gradually dropped along the four-stage biofilm system where anoxic and subsequent aerobic reactors were the major contributor of the overall organic removal, yet anaerobic process only played a minor role in COD removal. Organic matters removal efficiencies during the experimental periods were steadily maintained almost over 75 % with the influent COD between 1000-1200 mg/L, accordingly, final effluent COD concentrations were less than 300mg/L, even at rather short HRT of 45h, indicating the FB-A^2/O^2 system possessing a strong adaptive ability to the organic loading shock. Nevertheless, NH_4^+-N removals were almost entirely occurred at aerobic stages, especially in the second aerobic bioreactor and NH_4^+-N seemed to some extent increased in the anaerobic/anoxic reactors. Ammonia nitrogen removal efficiencies drastically varied between 23.1 % and 99.4 % among different experimental runs greatly influenced by HRT.[1, 2, 7]

In Run 1, average COD and NH_4^+-N in the final effluent dropped to 123 mg/L and 0.7 mg/L, respectively. In this case, 88.1 % COD and 99.4 % NH_4^+-N were removed at HRT of 136 h, concluding that COD and NH_4^+-N were thoroughly degraded at such an extremely long HRT. In Run 2, COD removal further increased to 92.3 % along with a slight decrease in NH_4^+-N removal (97.8%), correspondingly, effluent average COD and NH_4^+-N concentrations were 97.8 mg/L and 1.7 mg/L, respectively, which met the demand of the first level of the coking wastewater discharge standards (GB8978–1996). An obvious increase in organic removal was likely explained by the acceleration of biofilm renewals and weakening of media clogging effects at faster rising filtration velocity due to properly increased hydraulic loading. In Runs 3-5, however, effluent COD and NH_4^+-N considerably raise with further decrease of HRT, indicating that deteriorated treatment capacity perhaps attributed by breaking the biomass for media and lowering microbial activity due to stronger scour and shear at excessively shortened HRT.[35] Especially, it was found that NH_4^+-N removal efficiency was sharply reduced at shorter HRTs from 86 h to 46.5 h owing to detrimental effects of high organic loading on nitrification. Based on above results, the optimal total HRT of the integrated system seemed 116 h in this study.

The Figure 3 reveals the relationship between influent volumetric loadings and removed loading rates. In accord with other correlation studies,[36, 37] experimental data showed good linear correlations for both COD and NH_4^+-N between volumetric loading and removed loading at high correlation coefficient (R^2 above 0.9) with above 75% COD removal efficiency among 0.15~0.65 kgCOD/m^3·d and above 60% NH_4^+-N removal efficiency at 0.03~0.07 kg NH_4^+-N/m^3·d. Compared with treating medium and low-strength wastewater, such relatively low volumetric loading rates were required for the treatment of high-strength coking wastewater containing considerable complex compounds and toxic or harmful substances.[1, 38]

Bioreactor performance and microbial characteristics in Reactor A_1

In Reactor A_1, anaerobic fermentation mainly acted as the pre-treatment for complex and poorly degradable organic matters in the coking wastewater. Its efficiency depended on the increasing rate of BOD_5/COD (B/C ratio) in the anaerobic effluents,[4, 9] because some biodegradable organic compounds such as volatile fatty acids (VFA) and low molecular organics were produced at the bottom of Reactor A_1 based on partial scission of heterocyclic or polycyclic rings though transformation of macromolecular structure rather than excessive degradation of organics at shorter HRTs during hydrolysis-acidification, leading to enhanced B/C increasing ratio and indistinctive removal of COD. As shown in Fig.4, it was clearly observed that apparent differences in increasing rate of B/C ratio and COD removal in anaerobic reactor at different HRTs. It was interesting that B/C ratios distinctly increased but COD was not largely removed at Runs 2 and 4 occurring favorable hydrolysis-acidification performance, while slight rises in B/C ratios but notable COD removals instead at three other runs, concluding that pretreatment efficiency was strongly influenced by anaerobic HRT. In this study, anaerobic HRT of 20 h seemed optimum for hydrolysis-acidification with 175 % increasing rate of B/C ratio and only 14.6 % COD removal at Run 2. It was concluded that anaerobic HRT optimization played an important role in enhancing hydrolysis-acidification efficiency to improve the biodegradability of coking wastewater and provide enough readily biodegradable organics for subsequent anoxic and aerobic treatment processes,[26] while increasing-efficiency in B/C ratio was greatly low at short HRT due to incomplete transformation of refractory compounds (Run 1) or at too long HRT owing to excessive mineralization of biodegradable organics (Runs 4-5). The performance of the anaerobic biofilm reactor was also confirmed by its microbial characteristics, because a mass of facultative anaerobic bacteria commonly found in anaerobic wastewater treatment systems such as *Bacillus*，*Aeromonas*, *Flavobacterium* and *Paracoccus* (in Fig.5 a-d) which were capable of performing hydrolysis-acidification effect were identified.

Bioreactor performance and microbial characteristics in Reactor A_2

Figure 6 depicts DO, COD, NH_4^+-N and NO_3^--N profiles along the height of Reactors A_2

at different HRTs. It was clearly that the submerged fixed bed with granular filter media had uneven spatial distribution characteristics in oxygen, carbon and nitrogen, unlike complete-mixing reactors. Sudden drops in DO and COD were evidently observed at the initial of the packing layer height (at 0.2 m) due to abundant organic substrates rapidly utilized by higher biomass at the bottom of the reactor.[31, 39] Similarly with DO and COD, concurrent decreasing trends of NH_4^+-N and NO_3^--N implied that organic removal, nitrification and denitrification occurred simultaneously at the bottom, closely linked with diverse microbial populations. And then COD and NO_3^--N at the upper part of the reactor were concurrently removed by denitrification along the height of above 0.2 m at gradual decreased DO, partly preventing adverse impacts of high oxygen concentration from internal recycling liquid on anoxic denitrification based on continuous plug-flow characteristics of the granular fixed bed reactor.[39, 40] But NH_4^+-N converted by organic nitrogen and cyanide compounds (CN^-) increased above 0.2 m due to ammonification.[41] Furthermore, DO profiles among different runs were closely related with HRT, longer HRT led to higher DO due to low loading rates. Carbon and nitrates removal rates at short HRT (Runs 2 and 4) were higher than at very long HRT (Run 1), because excessive nitrates were accumulated, causing insufficient denitrification due to low C/N ratio and higher nitrate loading. On the other hand, organics and nitrogen were poorly removed at too short HRT because of low degrading speeds at high volume loading rates. Thus, appropriate control of HRT could improve simultaneous carbon and nitrogen removals, especially enhance anoxic degradation of refractory organic compounds under the denitrifying condition at the presence of NO_3^--N.[29, 42, 43] In this study, about 134 mg/L COD and 35 mg/L NO_3^--N were simultaneously removed via almost complete denitrification at the optimal anoxic HRT of

32 h at Run 2. Compared with conventional biological processes,[1, 10, 44] COD/NO_3^--N ratio was just only about 3.8 for thorough denitrification, demonstrating that internal carbon source was greatly economized in the FB-A^2/O^2 system to treat coking wastewater with low B/C and C/N ratios. A large number of observed organisms in the anoxic reactor at Run 2 were identified as *Alkaligenes*, *Pseudomonas stutzeri*, *Flavobacterium* and other bacilliform facultative bacteria in Fig.7 a-c, some of which were heterotrophic nitrifying and anoxic/microaerophilic denitrifying bacteria[45, 46] coexisting in the single anoxic reactor under abundant organic substrates, resulting in significantly removing nitrogen.

Bioreactor performance and microbial characteristics in Reactors O_1 and O_2

The Figure 2 showed that COD was mostly removed in Reactor O_1 due to aerobic oxidization by heterotrophic bacteria and NH_4^+-N was slightly removed because autotrophic nitrifiers such as AOB and NOB tended to fail to compete with other heterotrophic bacteria at higher COD loading and toxicity, while nitrifying bacteria could easily occupy predominance to significantly remove NH_4^+-N at lower organic loading in Reactor O_2.

In Fig. 8, similarly in the Reactor A_2, obvious variations were presented in oxygen, organic and nitrogen concentrations profiles along the Reactor O_2 height at different HRTs due to identical reactor configuration and operational pattern. DO levels strongly affected by HRT almost linearly dropped along the reactor height due to vertical distribution characteristics created in the up-flow fixed bed reactor filled with granular filter media.[39, 40] COD concentrations swiftly decreased at 0.6 m at the bottom of the reactor due to quick degradation of biodegradable organic matters via higher biomass, while NH_4^+-N concentrations reduced drastically along with continuous nitrates accumulation at the upper part of the reactor, especially above 1.2 m, implying significant nitrification performed by enough autotrophic nitrifying bacteria, which were dominant bacterial groups due to lack of available biodegradable organics at the upper and top height. As Fig.8 shown, remarkable NH_4^+-N removal were achieved at Runs 1 and 2 due to long HRT and low organic loading, while ammonia were poorly removed at Run 4 owing to limited nitrification by high organic loading. Consequently, it was concluded that suitable selection of HRT was essential for efficiently removing nitrogen from coking wastewater.

In terms of microbial characteristics in aerobic reactors, aerobic heterotrophic microorganisms including *Bacillus, Flavobacterium, Zoogloea* and *Nocardia* (Fig.9 a-d) existed in Reactor O_1, while autotrophic nitrifying bacteria such as *Nitrobacter*, *Nitrococcus*, *Nitrosomonas* and *Nitrosococcus* (Fig.10 a-d) outgrown by heterotrophs under lower organic loading were dominant bacteria in Reactor O_2, consistent with operational characteristics and process efficiencies of two-step aerobic treatment system.

Conclusions

Bioreactor performance and microbial characteristics in a novel pilot-scale four-stage biofilm anaerobic/anoxic/oxic/oxic (FB-A^2/O^2) system to steadily enhance the treatment of coking wastewater treatment were specifically investigated at various HRTs. Through optimization, the best coking effluent quality was obtained at 116 h achieving the total 92.3 % COD removal and 97.8 % NH_4^+-N removal efficiencies at rather low volumetric loading rates due to complex composition and high toxicity of the wastewater. Some dominant bacterial populations related with bioreactor performance were also identified by pure culture and microbial analysis, implying hydrolysis-acidification, denitrification, carbonization and nitrification were integrated within a system to efficiently treat poorly degraded and highly toxic coking wastewater.

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Fig.1 Schematic diagram of a pilot-scale A^2/O^2 biofilm system (a) process chart; (b) actual system; (c) packing media.

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Fig.10 Morphology of dominant bacteria in Reactor O_2 (a: *Nitrobacter*; b: *Nitrococcus*; c: *Nitrosomonas*; d: *Nitrosococcus*).

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Table 1. Specification of the used bio-packings

Specification	Hollow plastic balls	Ceramic particles
Type	Ball	Granular
Specific surface area (m^2/m^3)	236	3900
Porosity (%)	90%	≥55%
Hydrochloric acid soluble rate (%)	≤0.22	≤0.22
Sodium hydroxide soluble rate (%)	≤15.0	≤15.0
Diameter (mm)	50	3-7

Table 2. Characteristics of influent coking wastewater

Parameter	Unit	Average value	SD,standard deviation	N,sampling number
pH	—	8.3	0.3	32
BOD_5	mg/L	303	61	24
COD	mg/L	1195	297	30
BOD_5/COD	—	0.23	0.07	18
NH_4^+-N	mg/L	228.2	55.5	32
Phenol	mg/L	255	117	5
Cyanide	mg/L	8	2	5

Table 3 Operational conditions under different experimental stages

Run	COD (mg/L)	NH_4^+-N (mg/L)	HRT(h)	Operation periods (days)
1	1036±42	233.9±9.7	174	49
2	1230±231	278.6±51	116	63
3	1046±73	221.8±32.5	87	49
4	1212±95	147.5±26.6	69.6	42
5	1079±79	227.2±23.2	43.5	64

Table 4 Culture medium

Microorganisms	Culture medium containing (per liter)
facultative anaerobic bacteria	glucose 10.0 g, beef extract 10.0 g, peptone 10.0 g, NaCl 10.0 g, AGAR powder 20.0 g with distilled water1000 mL and pH 7.0.
aerobic heterotrophic bacteria	beef extract 10.0 g, peptone 10.0 g, NaCl 10.0 g, AGAR powder 20.0 g with distilled water 1000 mL and pH 7.0.
nitrite bacteria	NaCl 0.3 g, $MgSO_4{\cdot}7H_2O$ 0.14 g, $FeSO_4{\cdot}7H_2O$ 0.3 g, KH_2PO_4 0.14 g, $(NH_4)_2SO_4$ 0.66g, $CaCO_3$ powder 6.0 g, AGAR powder 20 g, trace elements solution[a] 0.4 mL with distilled water 1000 mL and pH 7.2.
nitrate bacteria	NaCl 0.3 g, $MgSO_4{\bullet}7H_2O$ 0.14 g, $FeSO_4{\bullet}7H_2O$ 0.3 g, KH$_2$PO4 0.14 g, $(NH_4)_2SO_4$ 0.66g, $NaNO_2$ 0.5g, $CaCO_3$ powder 6.0 g, AGAR powder 20 g, trace elements solution[a] 0.4 mL with distilled water 1000 mL and pH 7.2.

[a] trace elements solution that consists of the following components (per liter): $ZnSO_4{\cdot}7H_2O$ 0.003g, $MnSO_4{\cdot}7H_2O$ 0.003g, $CoSO_4{\cdot}7H_2O$ 0.001g and $CuSO_4{\cdot}5H_2O$. 0.003g.

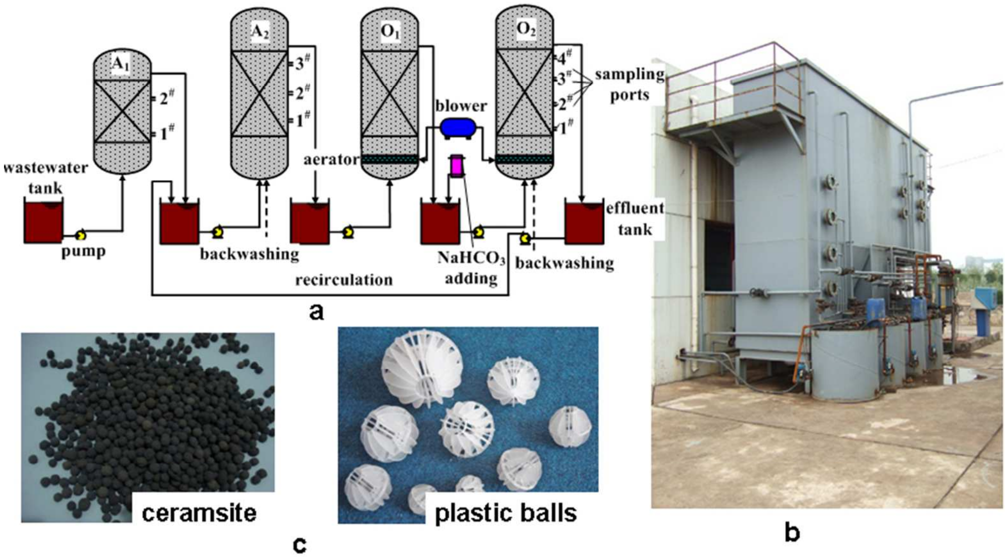

Fig.1 Schematic diagram of a pilot-scale A2/O2 biofilm system (a) process chart; (b) actual system; (c) packing media.
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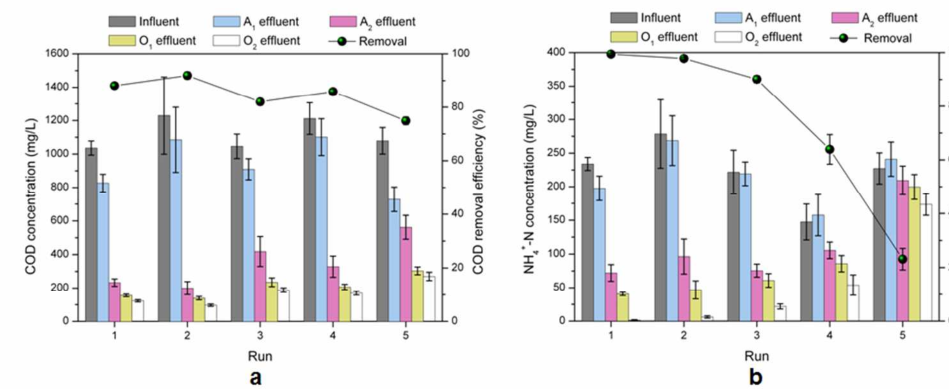

Fig.2 Average influent and effluent concentration and corresponding removal efficiency during operational periods (a) COD; (b) NH4+-N.
270x105mm (96 x 96 DPI)

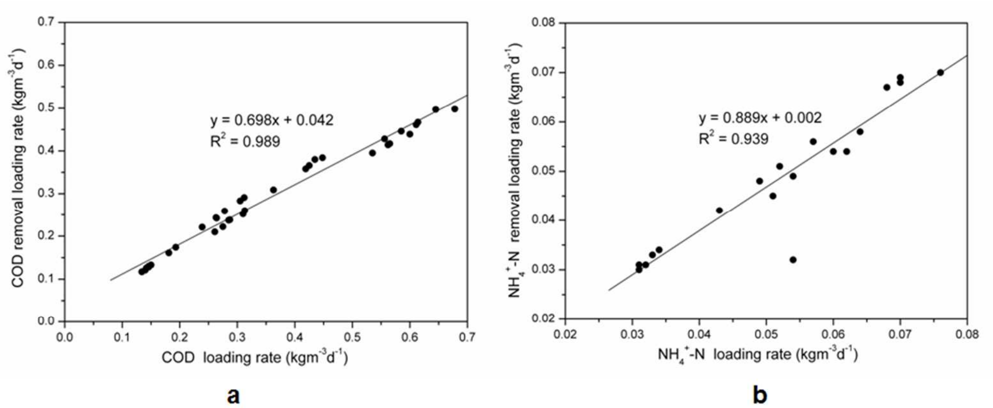

Fig.3 Relationship between influent volumetric loadings and removed loading rates (a) COD; (b) NH4+-N.
250x105mm (96 x 96 DPI)

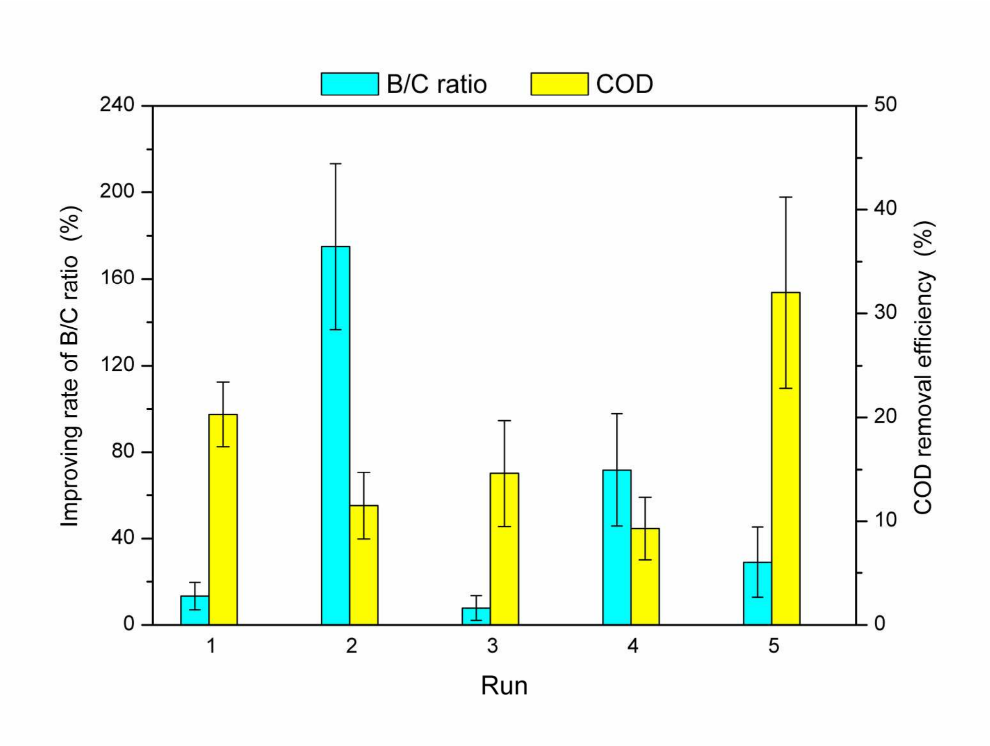

Fig.4 Increasing rates of B/C ratio and COD removals in Reactor A1.
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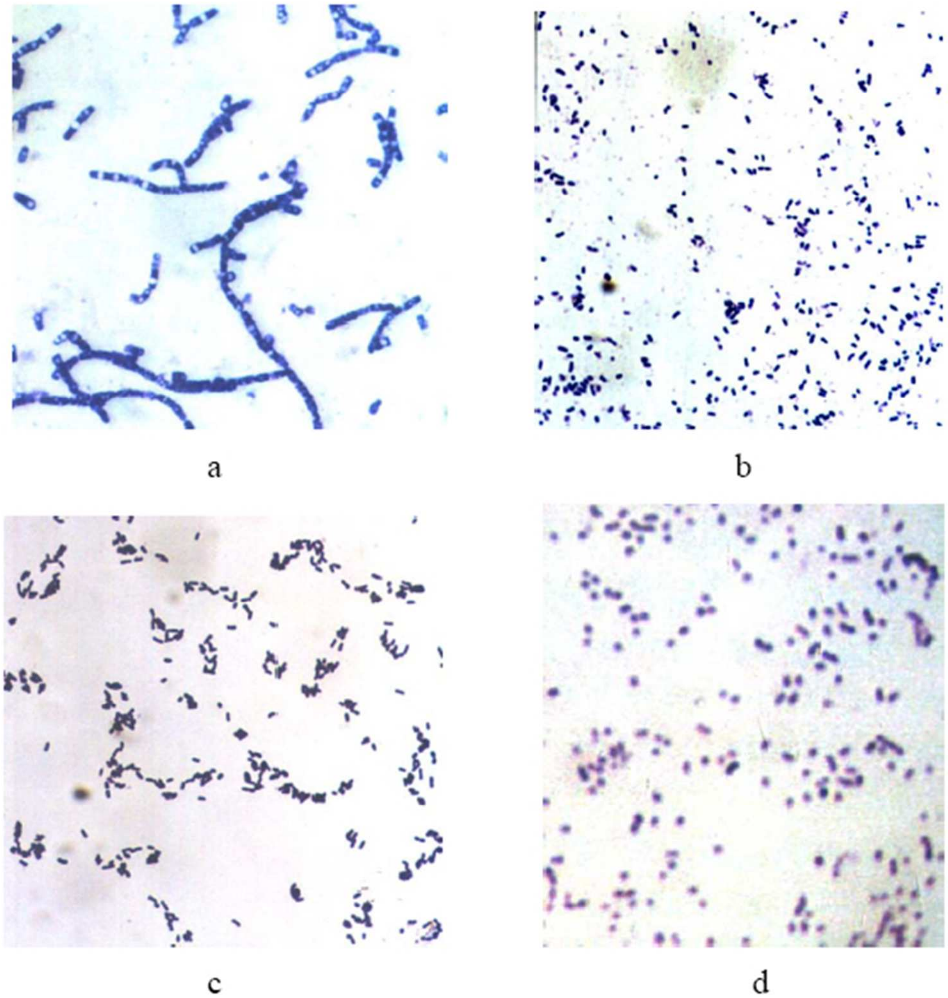

Fig.5 Morphology of dominant bacteria in Reactor A1 (a: Bacillus; b: Aeromonas; c: Flavobacterium; d: Paracoccus).

156x158mm (96 x 96 DPI)

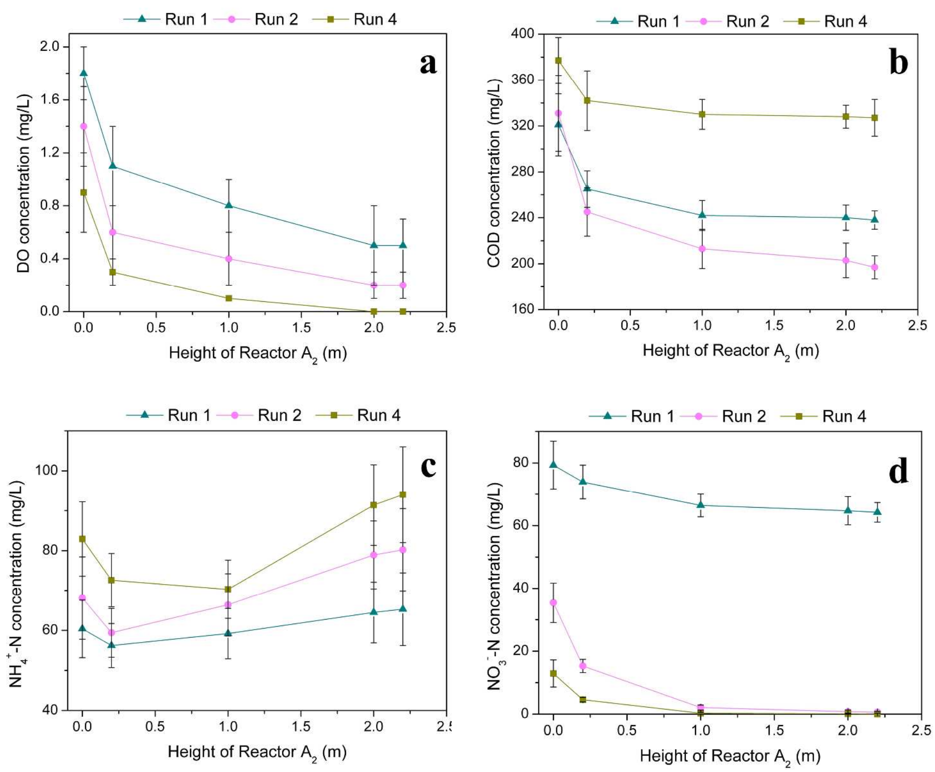

Fig.6 Concentration profiles along the height of Reactors A2 (a) DO; (b) COD; (c) NH4+-N and (d) NO3--N.

331x273mm (300 x 300 DPI)

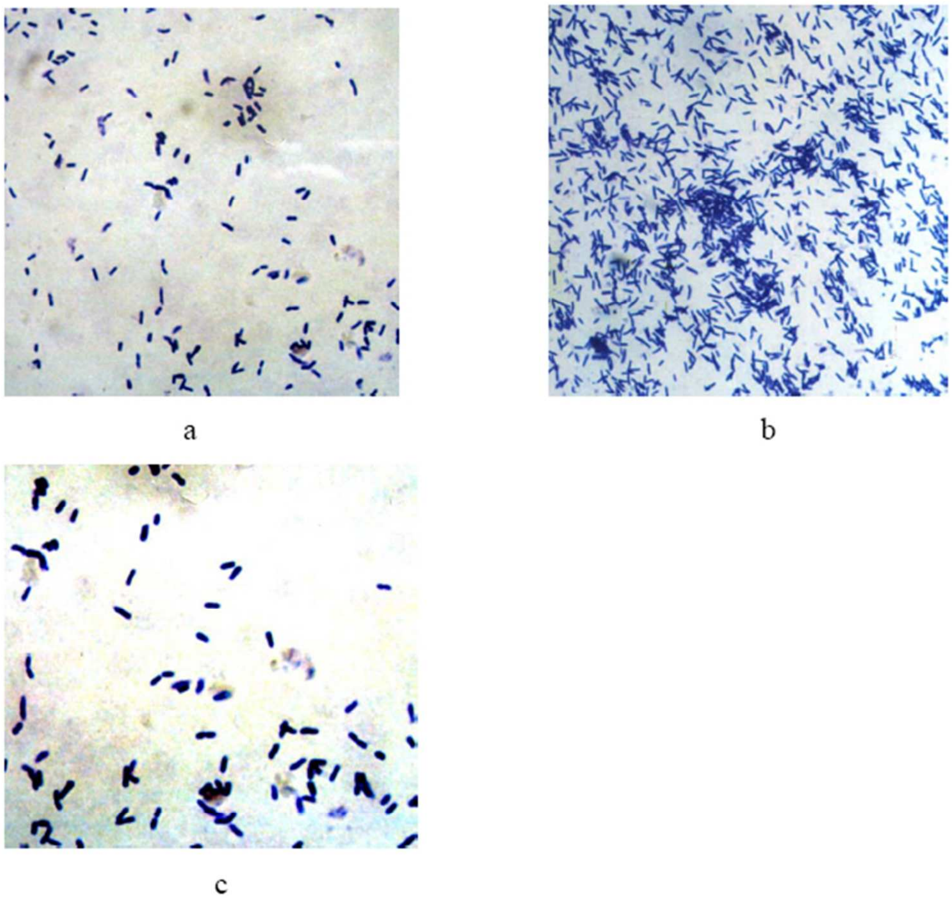

Fig.7 Morphology of dominant bacteria in Reactor A2 (a: Alkaligenes; b: Pseudomonas stutzeri; c: Flavobacterium).

170x156mm (96 x 96 DPI)

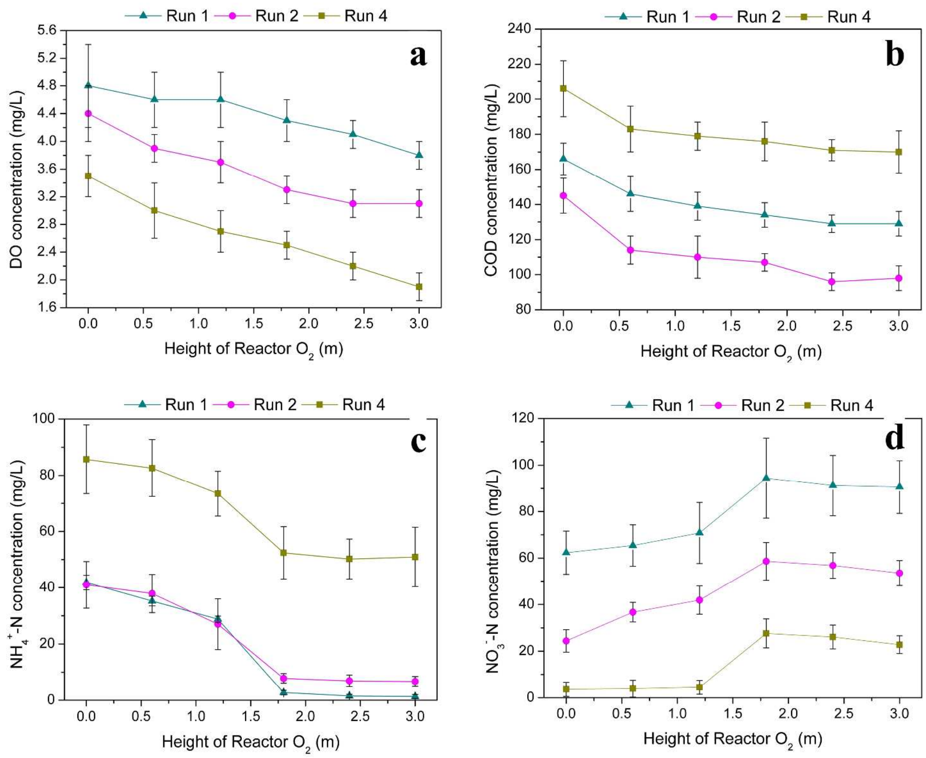

Fig.8 Concentration profiles along the height of Reactors O2 (a) DO; (b) COD; (c) NH4+-N and (d) NO3--N.

333x271mm (300 x 300 DPI)

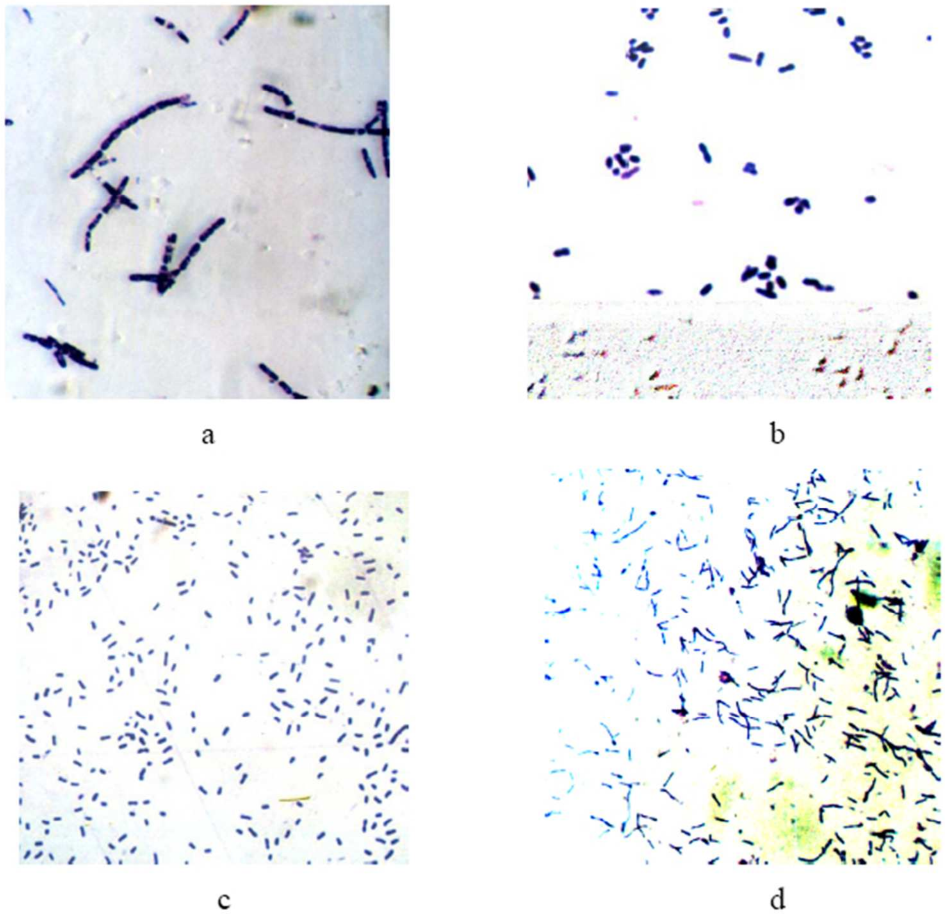

Fig.9 Morphology of dominant bacteria in Reactor O1 (a: Bacillus; b: Flavobacterium; c: Zoogloea; d: Nocardia).
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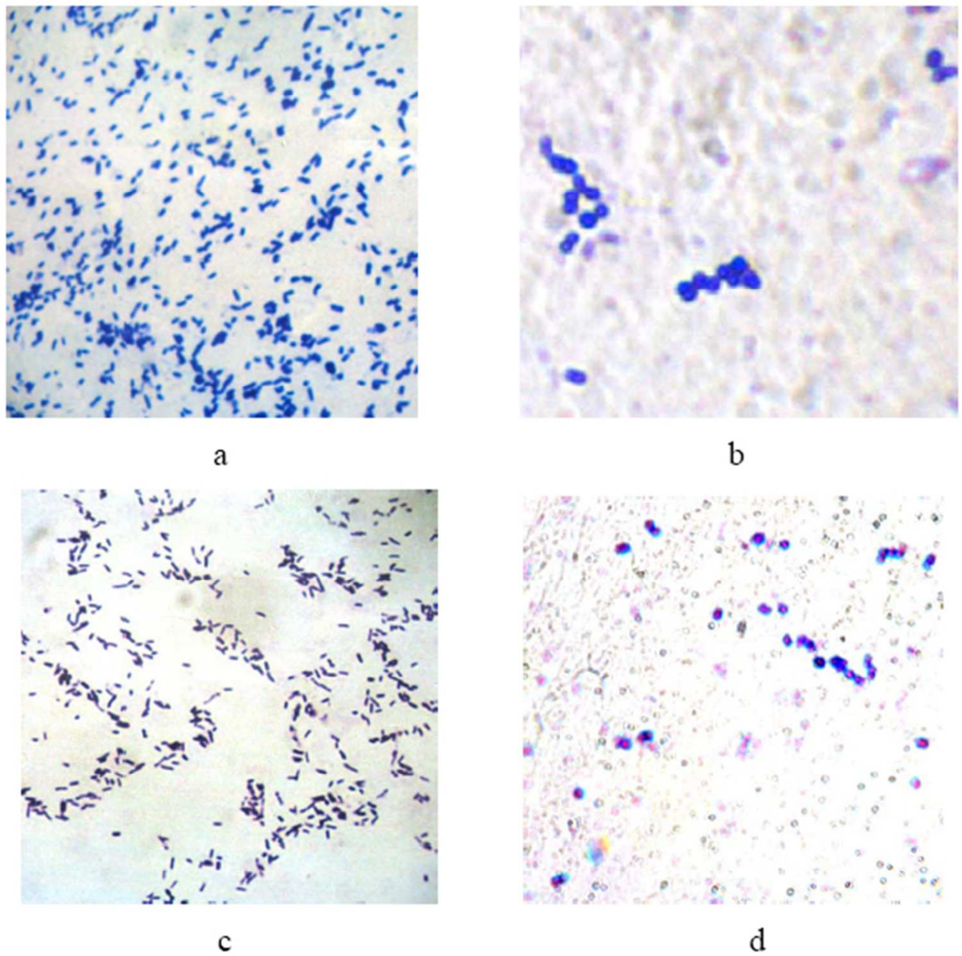

Fig.10 Morphology of dominant bacteria in Reactor O2 (a: Nitrobacter; b: Nitrococcus; c: Nitrosomonas; d: Nitrosococcus).
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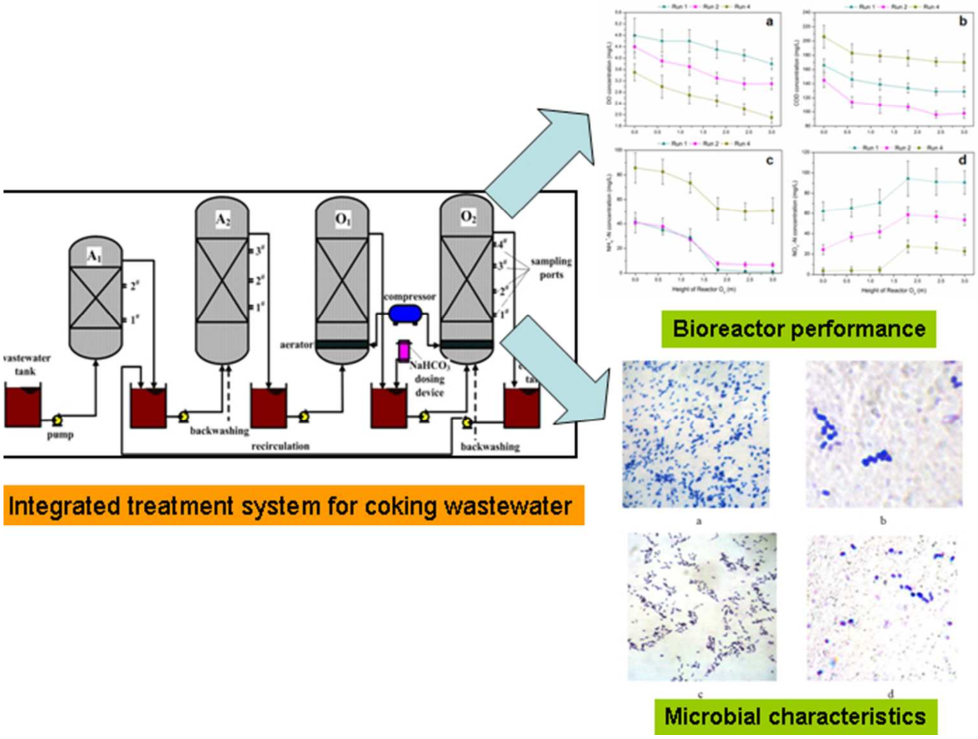

Graphical Abstract
188x138mm (96 x 96 DPI)