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Treatment and energy-consumption analysis of high-salt mustard wastewater using combined anaerobic, partial nitritation and ANAMMOX processes

Han Wang, Fang Fang*, Kai Li, Hui Xing, Jin-song Guo, You-peng Chen*
Lian-wei Liu, Zhen-guo Bao

Key Laboratory of the Three Gorges Reservoir Region's Eco-Environments of MOE, Chongqing University, Chongqing 400045, China, Tel. +86-15025487868, email: wanghan2202@163.com (H. Wang), Tel. +86-23-6512737, email: fangfangcq@cqu.com (F. Fang), Tel./Fax +86-23-6512737, email: kaicqu@126.com;phone (K. Li), Tel. +86-13657639770, email: xinghuiv587@126.com (H. Xing), 250633027@ qq.com (L.-W. Liu), 154282774@qq.com (Z.-G. Bao). Tel. +86 13908361681, email: Guo0768@cqu.edu.cn (J.-S. Guo), Tel. +86 13637820785, email: ypchen@cqu.edu.cn (Y.-P. Chen)

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ABSTRACT

Mustard wastewater has high concentrations of organic compounds, salt and ammonia. Treating this kind of wastewater using conventional treatment processes is difficult. New developments in sewage treatment processes are the current demand because the activated sludge process was invented more than 100 years ago. This study aimed to treat high-salt mustard wastewater using a combined process consisting of an anaerobic sequencing batch biofilm reactor for anaerobic digestion, a sequencing batch reactor for partial nitrification and an up-flow anaerobic sludge blanket reactor for anaerobic ammonia oxidation. To assess the energy consumption of the combined system, contrastive analysis of the traditional process was conducted. The COD and total nitrogen removal efficiencies reached 96.7% and 87.5%, respectively, in the combined process with an average salinity concentration [NaCl, w/v] of 16.5 g/L. Therefore, this combined processes can treat high-salt mustard wastewater and is more energy saving, environmentally friendly and economical than traditional nitrification/denitrification processes.

Keywords: Partial nitritation; ANAMMOX; Salinity; UASB reactor; Mustard wastewater

1. Introduction

Mustard is a well-known pickle from China and shares a common reputation with German salted and French pickled cucumbers. Annually, mustard production emits approximately 5 million m^3 of mustard wastewater in the Three Gorges Reservoir Area, which include high inorganic compounds, salt and ammonia, therefore difficult to treat biologically.

New developments in the sewage treatment process are needed after more than 100 years since activated sludge process was invented. The treatment process should be energy saving, emission reducing, and resource recycling [1]. Activated sludge method has been successfully applied in treating saline wastewater; however, altered salt concentrations disrupt biological activity, reduce degradation kinetics and cause poor sludge-settling characteristics [2]. Moreover, researches in these points are lacking. The high amount of salts during wastewater treatment may adversely affect the biological processes in the treatment systems [3,4]. Although salt inhibits the process of wastewater treatment, salt stress may be alleviated by adopting two strategies, namely, (1) enrichment of halophilic organisms from brackish and marine sediments [5] and (2) gradual acclimatisation of freshwater sludge to high saline conditions [5–7]. Woolard et al. [8] studied a moderate halophile isolated from the Great Salt Lake, UT,

*Corresponding author.

fangfangcq@cqu.edu.cn; ypchen@cqu.edu.cn

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USA. Their study achieved an average phenol removal of more than 99.5% in a SBR operated with 15% salt during a 7-month study period. Kim et al. [9] slowly adopted a lab-scale rotating biological contact reactor operated under oxygen-limited autotrophic nitrification/denitrification conditions for 178 days to increase salt concentrations up to 30 g/L (NaCl). The reactor performed well during the experimental period.

To exploit new energy-saving and emission-reducing treatments in dealing with mustard wastewater, new nitrogen removal processes are being considered. Anaerobic ammonium oxidation (ANAMMOX) is an environmentally friendly and cost-effective technology with nitrogen-removal potential [10–12] and does not require organic compounds [13,14]. Therefore, using ANAMMOX to treat wastewater is suitable for the aforementioned concept. Nitrogen in the mustard wastewater, rather than organic compounds, can be removed by ANAMMOX. Moreover, most organic compounds can be removed by anaerobic process, which can reduce adverse effects on ANAMMOX; besides, organic nitrogen in mustard wastewater can also be converted into ammonia nitrogen. Nitrogen exists in the form of ammonia nitrogen, which is not susceptible to ANAMMOX. Therefore, a partial nitritation (PN) process that can transform partial ammonia nitrogen into nitrite is required. The objective of this study was to attempt to evaluate the possibility of using the combination of anaerobic digestion, PN and ANAMMOX in treating high-salt wastewater.

Anaerobic digestion in anaerobic sequencing batch biofilm reactor (ASBBR) is essential for the removal of COD, then PN and ANAMMOX process was implemented in a sequencing batch reactor (SBR) and up-flow anaerobic sludge blanket (UASB) reactor, respectively, to remove ammonia nitrogen. To successfully process the combination, our strategy was to launch three reactors respectively and thereafter the three processes were combined. For ASBBR and SBR, the strategy of gradient dilution with raw mustard wastewater was adopted. For better and faster start-up of UASB reactor, synthetic wastewater was used instead of raw mustard wastewater. In this study, the start-up of UASB reactor, which was the key to the research, was investigated. The performance of the combined processes was evaluated to determine its effects. Moreover, to assess energy consumption of the combined processes, comparison with traditional processes was conducted with blasting aeration.

2. Materials and methods

2.1. The characteristics of wastewater

High-salt wastewater was obtained from Fuling District, China, which is a pickle industry base with a long history. Table 1 shows the characteristics of the raw wastewater in this study. The ratio of COD to total nitrogen (TN) to total phosphorus was 111:7:1, which was practical for an anaerobic digestion. The pH value of the wastewater was low and therefore adjusted before being pumped into the combined process.

Table1
The characterisation of high-salt raw mustard wastewater

Parameters	Range	Mean
Chemical oxygen demand (mg/L)	3880~4120	4010
Total nitrogen (mg N/L)	225~250	236.0
Ammonium nitrogen (mg N/L)	80~130	105.0
Nitrate nitrogen (mg N/L)	12~28	18.0
Nitrite nitrogen (mg N/L)	0.0	0.0
Total phosphorus (mg P/L)	30~40	37.0
pH	5.9~6.5	6.2
NaCl (w/v)	/	16.5 g/L

2.2. The experiment of reactor (ASBBR) start-up

2.2.1. Reactor

Anaerobic digestion was performed in a cubical ASBBR made with polyvinyl chloride that had an effective volume of 40 L. Nine pieces of combined soft-packing was used as biomass carrier in the reactor (Fig. 1a). The seed sludge was derived from an anaerobic digester which employs anaerobic/anoxic/oxic (A2/O) process in a sewage treatment plant in Chongqing. The MLSS and MLVSS concentrations of these seed sludge were 7.82 and 4.56 g/L, respectively. A total of 15 L seed sludge was put into the ASBBR. A 24-hour working cycle was applied through the whole operation period. The feed and discharge were both instantaneous. The exchange volume was 50%, resulting in a hydraulic retention time (HRT) of 48 h. The water temperature was maintained at 31 ± 1°C by an electric heating rod and the pH value was controlled at 7.1 ± 1 by using 1 mol/L NaOH and HCl solution.

2.2.2. The strategy for ASBBR start-up

The influent was raw mustard wastewater; however, during the ASBBR start-up, it was diluted into five dilution gradients, namely, 10-fold, 5-fold, 2.5-fold, 1.25-fold and 0-fold. The initial conditions were: salinity, 1.6 g/L; total nitrogen, 28 mg/L; ammonia nitrogen, 15 mg/L; and nitrate nitrogen, 3 mg/L. To better adapt to salinity, halophilic bacteria were isolated from the inoculated sludge. After a massive culture, they were added into the reactor.

In the start-up process, the COD removal efficiency and effluent NH_4^+-N/TN ratio was used as the main control index. A standard was defined similarly when the COD removal efficiency was above 70% and the effluent NH_4^+-N/ TN ratio was above 90% the reactor was considered stable. After running stable at initial dilution, the influent was turned into the next dilution until the influent was undiluted raw mustard wastewater. To compensate for the lower COD concentration for dilution, glucose and peptone were added to the influent to maintain a COD concentration of 1300 mg/L. Finally, the reactor ran continuously with raw mustard wastewater until three processes were combined.

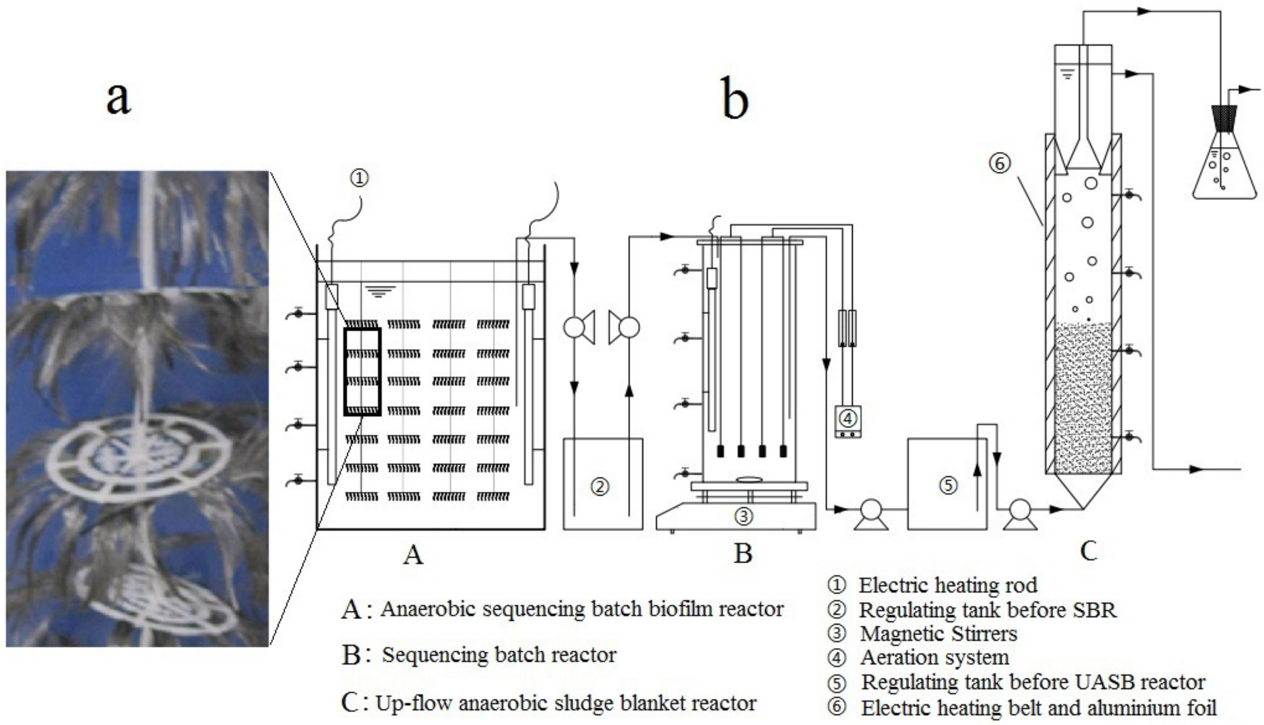

Fig. 1. Image of the carrier in ASBBR (a) and schematic diagram of combined system (b).

2.3. The experiment of SBR start-up

2.3.1. Reactor

PN was performed in a cylindrical Plexiglas SBR with a working volume of 10 L. The influent and effluent waters were intermittent and controlled by two peristaltic pumps. Oxygen was supplied by an air pump through four porous stone diffusers. The oxygen diffusers were coupled with magnetic stirrers to promote the formation of small bubbles and guarantee complete mixing. A heating rod was used to keep the temperature constant. The seed sludge was derived from an aerobic tank which employs anaerobic/anoxic/oxic (A2/O) process in the aforementioned sewage treatment plant. A total of 3 L seed sludge was put into the SBR after two weeks of aeration, with the MLSS and MLVSS at 19.82 and 10.69 g/L, respectively.

2.3.2. The strategy for SBR start-up

During ASBBR start-up, the influent of SBR also was raw mustard wastewater that was diluted into four dilution gradients, namely, 5-fold, 2.5-fold, 1.25-fold and 0-fold. The ammonium nitrogen concentration was maintained at 200 mg/L by adding $(NH_4)_2SO_4$.

Start-up of PN consisted of two stages: (i) complete nitrification; and (ii) PN. A 12-hour cycle was used throughout the whole set-up process. One cycle consisted of four successive phases, including: (1) 20 min feeding, (2) 600 min aeration and stirring, (3) 80 min settling and (4) 20 min discharging. The exchange volume was 50%. The DO level was kept at 0.2–0.5 mg/L during the operation, which was suitable for ammonia-oxidising bacteria (AOB) growth. In this optimal concentration, nitrite-oxidising bacteria (NOB) could live in a DO-limited environment. The temperature of the sludge suspension was maintained at 30±1°C. The SRT was maintained at approximately 30 d. The pH was kept at 8.0±1 using $KHCO_3$ solution. Upon start-up of the SBR, it routinely runs under the final conditions until the process combination is complete.

2.4. The experiment of UASB reactor start-up

2.4.1. Reactor

The ANAMMOX process was performed in a Plexiglas UASB reactor (160 cm in height, 10 cm in diameter). It had an active volume of 12 L consisting of a reaction zone volume of 9.65 L and a sediment zone volume of 2.35 L. Influent was introduced into the bottom of the reactor using a peristaltic pump, and effluent flowed out from the top. The produced gaseous N_2 was separated by a three-phase separator which then flowed through a pipe. An electric heating belt winded the reactor to keep the temperature constant. To prevent the light inhibition, aluminium foil was used to pack the reactor.

2.4.2. The strategy of UASB reactor start-up

Anaerobic ammonium-oxidising bacteria was sensitive to the environment and matured slowly; therefore, at the start-up, the influent of UASB reactor was synthetic and was different from those of ASBBR and SBR. It was composed as described by literature [15]. The initial concentrations of NH_4^+-N, NO_2^--N and NaCI were 28 mg/L, 36.4 mg/L and 0 g/L. As time passed, the concentrations of NH_4^+-N, NO_2^--N and NaCl improved gradually. When TN removal efficiency was above 80% as it turned to enter the next phase.

The seed sludge was a mixture that included anaerobically digested and aerobic sludge from the aforementioned sewage treatment plant with a volumetric ratio of 2:1. The MLSS and MVLSS of the anaerobically digested sludge were 6.050 and 3.520 g/L, respectively; and those of aerobic sludge were 0.798 and 0.502 g/L, respectively. Finally, 6.0 L of the mixed sludge was seeded.

The set-up of UASB reactor included four phases: (i) acclimation without salinity; (ii) acclimation with low salinity; (iii) elevating nitrogen loading rate; (iv) elevating salinity. The reactor was operated at a constant temperature (32°C) with a flow rate of 6.37 cm/h. The pH value was kept at 7.9–8.0 using $KHCO_3$ solution and HRT was 24 h.

2.5. The experiment of combined processes

Fig. 1b shows the experimental system consisting of ASBBR, SBR and UASB reactor. The raw wastewater was passed through the ASBBR to convert most of the organic nitrogen to ammonium. The effluent of ASBBR was then introduced into the SBR to convert half of the ammonium to nitrite and to obtain an appropriate ratio of ammonium to nitrite for anaerobic ammonium-oxidising bacteria (AnAOB). The SBR effluent was finally treated in UASB reactor by AnAOB.

AnAOB is sensitive to pH, therefore, the effluent pH values of ASBBR and SBR were adjusted by being flowed into regulating reservoir and then into the next reactor. Generally, a successful start-up of ANAMMOX process takes about 265 d; for the three reactors to be combined and deal with raw mustard wastewater (with a salinity of 16.5 g/L), the nitrogen loading rate (NLR) and salinity of UASB reactor should be increased, after start-up. The ASBBR and SBR were run steadily until the process combination. When the salinity and NLR were consistent with the raw mustard wastewater, the combination of process was executed.

2.6. Analytical methods

Samples were collected and analysed every four days in three reactors to evaluate the treatment performances of separate start-up phases; after they were combined data were measured once a day. Concentration measurements, including COD, TN, ammonium, nitrate, and nitrite, were done according to standard methods (China, 2002). Level of pH was determined using a portable digital pH meter (YSI pH100; YSI Co., USA). DO concentration and water temperature were measured using a portable DO meter (YSI Professional ODO™; YSI Co., USA). Salinity (NaCl, w/v) was calculated from the concentration of Cl^-, which was measured by ion chromatography.

Nitrite accumulation rate (NAR) was calculated as follows:

$$\mathrm{NAR}(\%) = \frac{\Delta c_{NO_2^- - N}}{\Delta c_{NO_2^- - N} + \Delta c_{NO_3^- - N}} \times 100\%$$

where $\Delta c_{NO_2^- \text{-} N}$ is the difference between nitrite concentrations in the influent and effluent, in mg/L; and $\Delta c_{NO_3^- \text{-} N}$ is the difference between nitrate concentrations in the influent and effluent, in mg/L.

3. Results and discussion

3.1. The performance of ASBBR and SBR in start-up phase

Start-up of ASBBR lasted approximately 85 d, with a COD removal efficiency of 87.5% and salinity of 1.65%, which indicated the adaptability of ASBBR in high COD and salinity. Gradient dilution method and in situ enrichment of halophilic bacteria may be the main driving factor.

The start-up of SBR succeeded after 125 d when the NAR was above 90%, which proved that the reactor has adapted to the salinity, indicating that PN can be conducted at a high salinity of 16.5 g/L.

3.2. The performance of UASB reactor in the start-up phase

The variation and removal efficiency of nitrogen compounds in the UASB reactor are shown in Fig. 2a and Fig. 2b respectively. The gradient of salinity, NH_4^+-N, NO_2^--N and NLR are shown in Fig. 3. The concentrations of salinity,

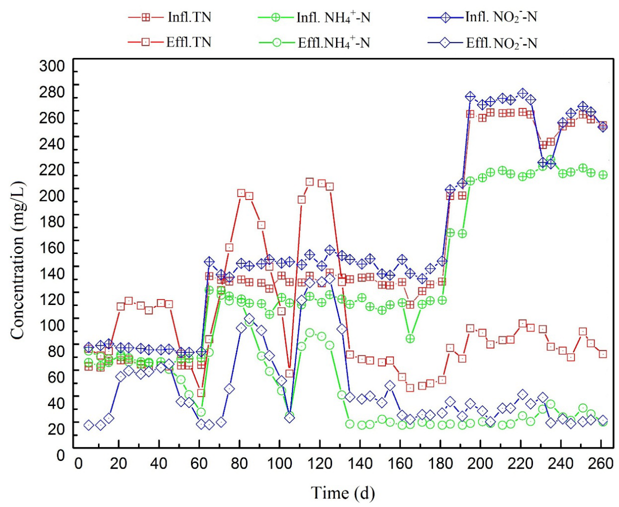

Fig. 2a. The variation of nitrogen compounds in the UASB reactor.

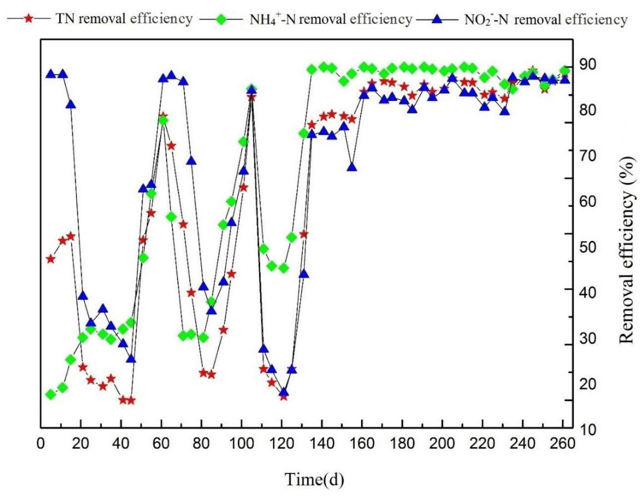

Fig. 2b. The removal efficiency of nitrogen compounds in the UASB reactor.

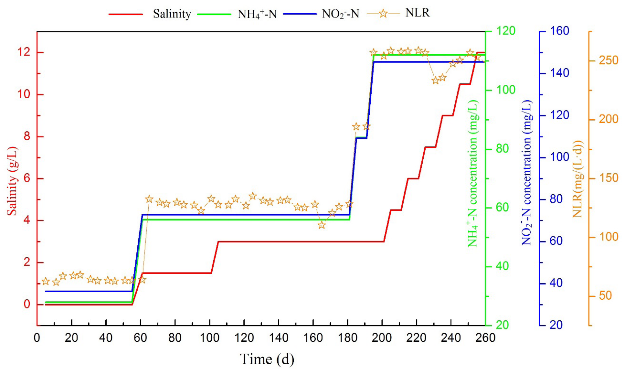

Fig. 3. The gradient of salinity, NH_4^+-N, NO_2^--N and NLR in the UASB reactor.

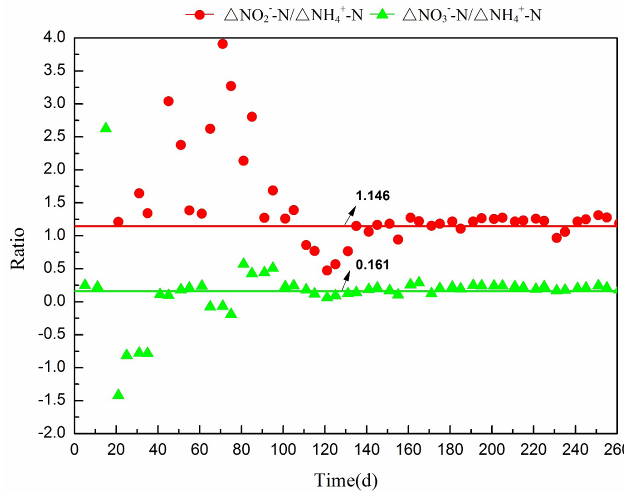

Fig. 4. The ratio of ΔNO_2^--N/ΔNH_4^+-N and ΔNO_3^--N/ΔNH_4^+-N in the UASB reactor.

NH_4^+-N and NO_2^--N improved gradually because AnAOB is sensitive to environmental factors (e.g. salinity). Firstly, there was a salt-free stage that lasted 60 days. In this stage, the concentration of influent TN showed an increase followed by a decline, which indicated denitrification. After the stage, the activity of ANAMMOX appeared slowly, which was evidenced by the decline of NH_4^+-N and NO_2^--N concentrations. The NH_4^+-N and NO_2^--N removal efficiencies were reduced twice, which indicated that improving salinity will adversely affect the ANAMMOX; however, the effect was withstood by the increase of NLR. InFig. 2b, approximately after the 265th day, the removals of TN, NH_4^+-N and NO_2^--N were all above 85%, signifying the success of the UASB reactor start-up.

To treat actual wastewater at a salinity of 1.65%, NLR and salinity were increased sequentially after 185 d. The scope of improving salinity and NLR was bigger than before, but the fluctuations of TN, NH_4^+-N andNO_2^--N were small. Moreover, Fig. 4 shows that the ratios of ΔNO_2^--N/ΔNH_4^+-N and ΔNO_3^--N/ΔNH_4^+-N were close to 1.146 and 0.161, which are the latest theoretical values modified by Lotti et al. [16] that is often seen as critical parameters for the efficient operation of ANAMMOX. This indicated that the acclimation of AnAOB with the increase of salinity and NLR can improve the ability of reactor to resist salinity to achieve treatment of mustard wastewater.

3.3. The performance of combination processes

After the 265th day, the three reactors were combined following the aforementioned strategy, the performances of COD removal and nitrogen conversion in the combined processes were assessed in detail.

3.3.1. COD removal

The performance of COD removal after combination is shown in Fig. 5a. The system was fed with diluted mustard wastewater, with a salinity of approximately16.5 g/L in 30 d. The COD concentration of the influent was higher than 3600 mg/L, and the effluent COD concentration was below 200 mg/L. These results indicated that the combined system was efficient in removing COD under the aforementioned salinity level.

Anaerobic digestion has important functions in COD removal. Although PN and ANAMMOX are both autotrophic, they also have a minor function in COD removal because of the complex environment. This phenomenon is shown in Figs. 5b and 6. Majority of the COD was removed in the ASBBR, which shared more than 91% of the total amount. The rest of the COD was removed through PN and ANAMMOX.

ASBBR is widely applied in COD removal. Siman et al. [17] reported that ASBBR is efficient and stable for COD loading rates of 1.5 g to 3.6 g COD/L/d. Their results showed that ASBBR with immobilised biomass is efficient for organic removal at an organic loading rate of 5.4 g COD/L/d. Moreira et al. [18] investigated the influence of organic shock loads in an ASBBR-treating synthetic wastewater. At operating concentrations of 500 mg to 1000 mg COD/L, the system regained stability after one cycle. These investigations showed the effectiveness and robustness of this type of bioreactor in COD removal when exposed to high COD loading rate and COD shock load. All of these studies were conducted without salinity. However, the present study demonstrated the possibility of anaerobic configuration application for the biological treatment of salt-rich wastewater.

During the system operation, Fig. 6 shows that PN and ANAMMOX removed approximately 9% of the COD. Wang et al. [19] reported the occurrence of simultaneous PN, ANAMMOX and denitrification in a single partially aerated full-scale bioreactor-treating landfill leachate. Therefore, the occurrence of denitrification was possible because the influent of SBR contained COD, which was not removed by ASBBR. The study of Wang et al. [19] also showed that AnAOB and AOB occurred in both nitritation/ANAMMOX granular sludge reactor and moving bed biofilm reactor. Oxygen uptake rate (OUR) tests also confirmed that flocculent biomass consists of a minor proportion of heterotrophy with a large proportion of AOBs. Therefore, heterotrophic AOBs may exist in UASB reactor, which can use the COD in the influent from SBR.

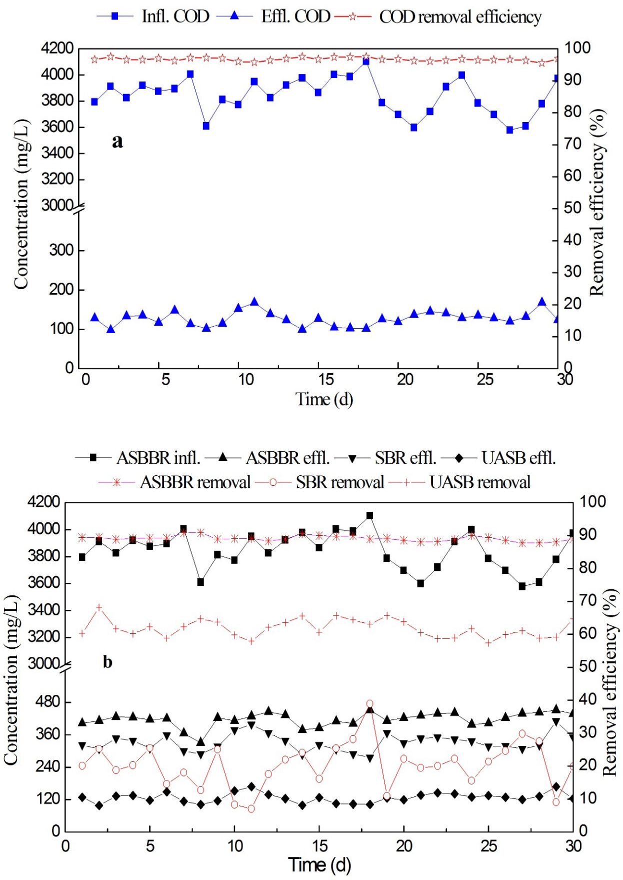

Fig. 5. (a) COD concentrations and removal efficiency of the system effluent (b) COD concentrations and removal efficiency of each reactor effluent.

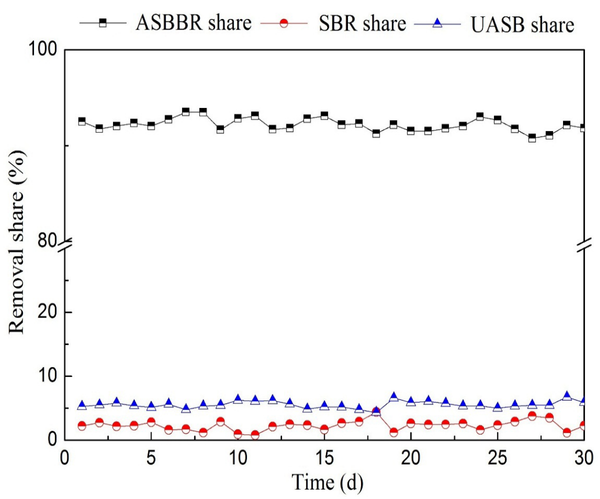

Fig. 6. COD removal share of each reactor.

3.3.2. TN removal

Fig. 7a shows the TN removal performance of the system. The combination of the three reactors removed 87.5% of TN on average. This system was efficient for TN removal under the salinity of 16.5 g/L. Ammonium and nitrite were

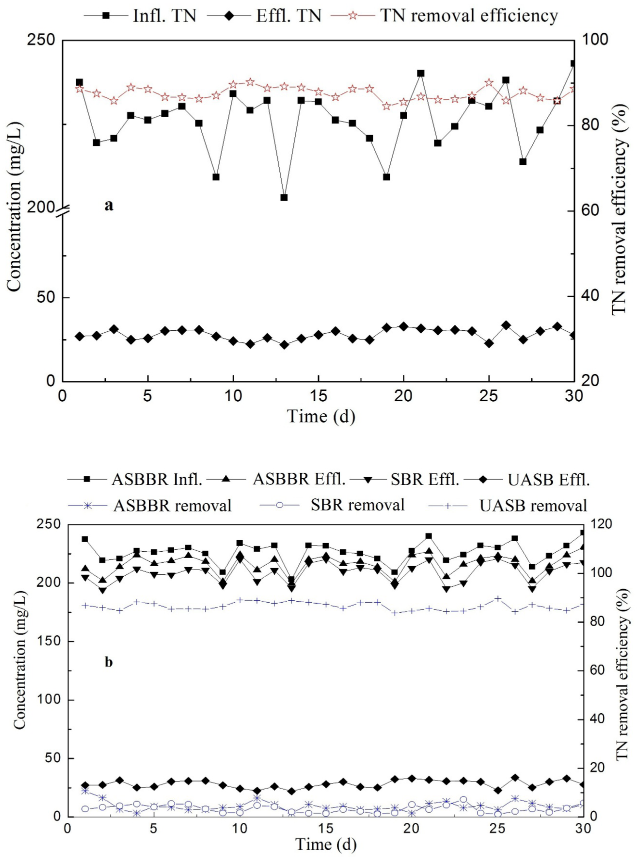

Fig. 7. (a) TN concentrations and removal efficiency of the system. (b) TN concentrations and removal efficiency of each reactor.

converted into nitrogen gas in UASB reactor by ANAMMOX, in which most of the TN in the system was removed and the rest of the TN was removed by ASBBR and SBR. This phenomenon is presented in detail in Figs. 7b and 8. The TN removal of ASBBR, SBR and UASB reactor were 4.5%, 3.3% and 86.5%, respectively, on average, which corresponded to 5.1%, 3.7% and 91.2% of TN on average.

ANAMMOX was the main part of the TN removal with a salinity of 16.5 g/L. Anaerobic biological treatment processes are known to be inhibited by salinity, but ANAMMOX is still promising for treating wastewater with high salinity [20]. Researchers have enriched AnAOB from marine sediment or acclimated freshwater AnAOB to higher salt concentrations [11,21]; moreover, ANAMMOX has been applied in salt-rich wastewater treatments. Mature landfill leachates present a high ammonium content and high salinity [22]. Anfruns et al. [23] evaluated the suitability to couple ANAMMOX with advanced oxidation processes (AOPs) to treat mature leachates with high nitrogen concentrations (230 ± 96mg/L, TN). The combination of a PN/ANAMMOX system coupled with two AOP-based technologies obtained a TN removal efficiency of 87%–89%. Dapena-Mora et al. investigated the performance of ANAMMOX in treating the effluent generated in an anaerobic digestion. The wastewater from a fish cannery was treated once previously in a single reactor system for high activity ammonia removal over nitrite reactor. The salinity (8

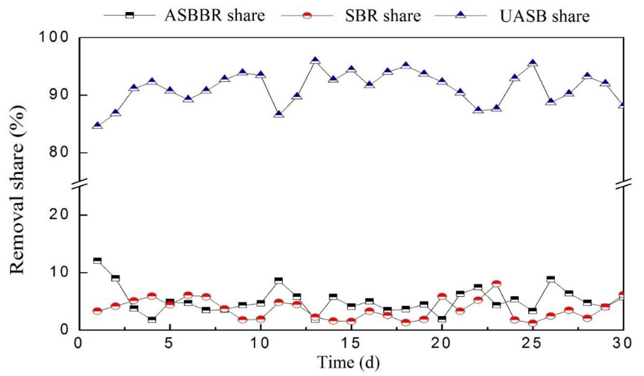

Fig. 8. TN share of each reactor.

g/L) of the system was raised to 10 g/L (NaCl). The system reached an average nitrogen removal efficiency of 68% [24]. The TN removal efficiency of this study was 87.5% on average, which was larger. These studies provided important evidence for the possibility of ANAMMOX application to remove nitrogen in salt-rich wastewater.

ASBBR and SBR both have limited contributions in removing nitrogen. In ASBBR and SBR, denitrification occurs because of the complicated microorganism system, in the presence of organic compound and nitrogen. Consequently, nitrogen is removed in the form of N_2.

3.3.3. Nitrogen conversion

3.3.3.1. ASBBR performance

During anaerobic digestion process, organic nitrogen is converted to ammonia [25]. The conversion of nitrogen is shown in Fig. 9a. The influent TN, ammonium and nitrate concentrations were 226.4, 81.9 and 17.1 mg/L, respectively, on average of and the effluent concentrations were 216.2, 214.5 and 1.2 mg/L. The data indicated that most organic nitrogen was converted to ammonia, and the TN concentration remained almost constant. Fig. 9b shows the ratios of ammonium to TN of the influent and effluent. The influent ratio of ammonium to TN was only 30%–35% and the ammonium accumulation efficiency was up to 95%–100% in the effluent. Thus, the performance of ASBBR was stable, and the effluent of ASBBR could meet the SBR requirement for PN.

3.3.3.2. SBR performance

PN is essential to provide an appropriate ratio of ΔNO_2^--N/ΔNH_4^+-N for ANAMMOX. The performance of SBR for PN is shown in Figs. 10a and b. The influent of SBR was from ASBBR, therefore, the ammonium concentration was 214.5 mg/L on average. Fig. 10a shows that approximately half of ammonium was converted to nitrite after PN. The effluent ammonium concentration was 96.2 mg/L. The nitrite concentrations of influent and effluent were 0 and 106.7 mg/L, respectively. Fig. 10b indicates that the ratio of ΔNO_2^--N/ΔNH_4^+-N was between 0.9 and 1.4 (between red lines), Tang et al. [12] reported that the ratio of ΔNO_2^--N/ΔNH_4^+-N in the influent was maintained at 1.0–1.2.

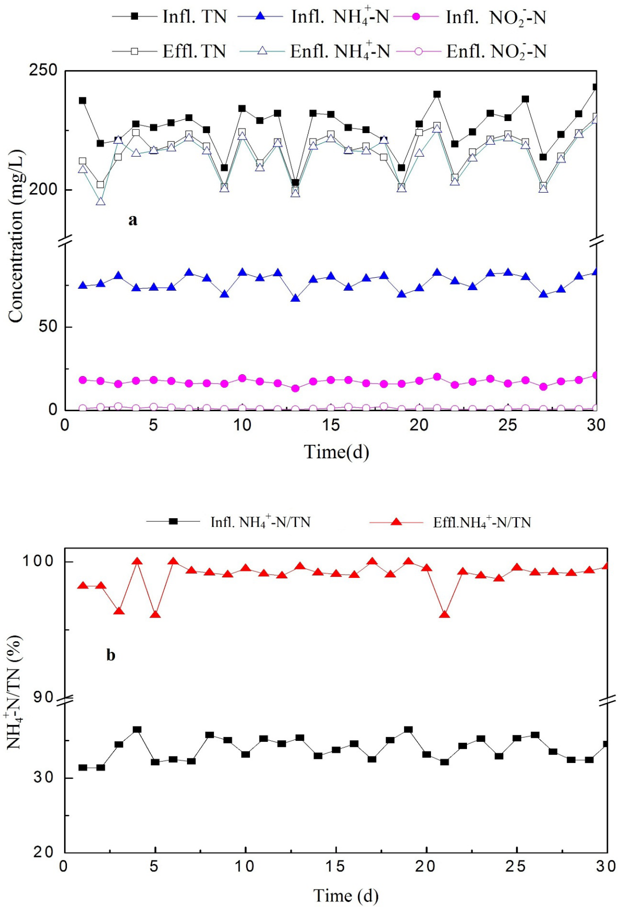

Fig. 9. (a) Profile of nitrogen conversion in ASBBR. (b) Profile of NH_4^+-N/TN ratio in ASBBR.

In the present study, the effluent ratio of ΔNO_2^--N/ΔNH_4^+-N fluctuated between 0.9 and 1.4 because the DO concentration was not constant in SBR. Jin et al. [26] stated that ANAMMOX biomass can over-ingest the extra substrate to a certain degree, i.e. 18.1% and 17.0% on average, during the periods of ammonium and nitrite excesses, respectively, which does not affect the performance of the next ANAMMOX process.

The DO concentration in SBR was maintained between 0.50 and 1.0 mg/L, which was suitable for AOB growth. In this optimal concentration, nitrite oxidising bacteria (NOB) could live in a DO-limited environment. Fig. 10a shows that the influent nitrate concentration was 1.2 mg/L, and the effluent concentration rose to 5.6 mg/L. Although NOB competed with AOB, Fig. 10b shows that the NAR could be still over 90%. This result showed that SBR performed well during the operation and could provide appropriate influent for UASB reactor.

3.3.3.3. UASB reactor performance

This combination process eliminated nitrogen and was achieved at UASB reactor. ASBBR and SBR were the bases for the influent quality of UASB reactor. Fig. 11a shows that the concentrations of ammonium, nitrite and

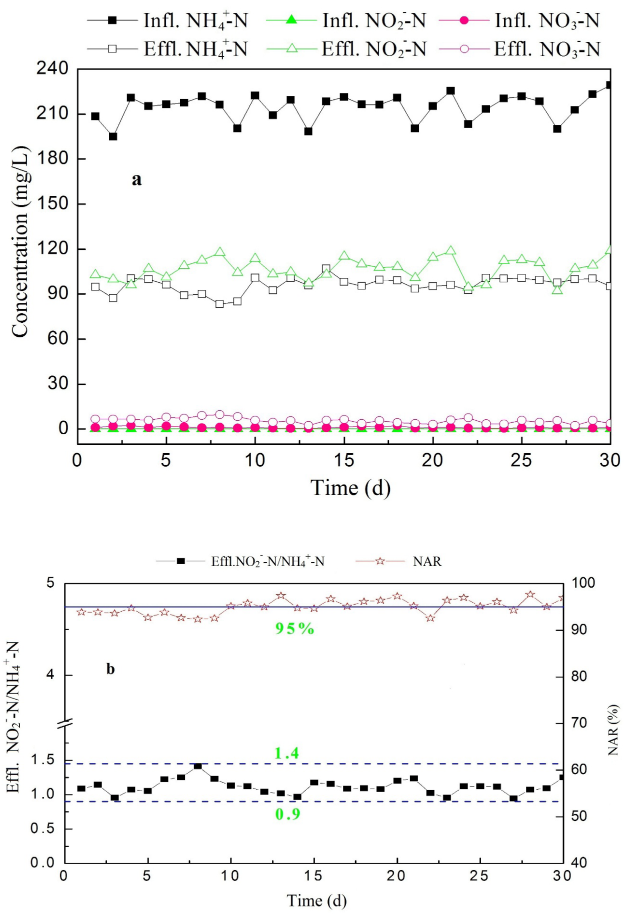

Fig. 10. (a) Profile of nitrogen conversion in SBR (b) Profile of NO_2^--N/NH_4^+-N ratio in SBR.

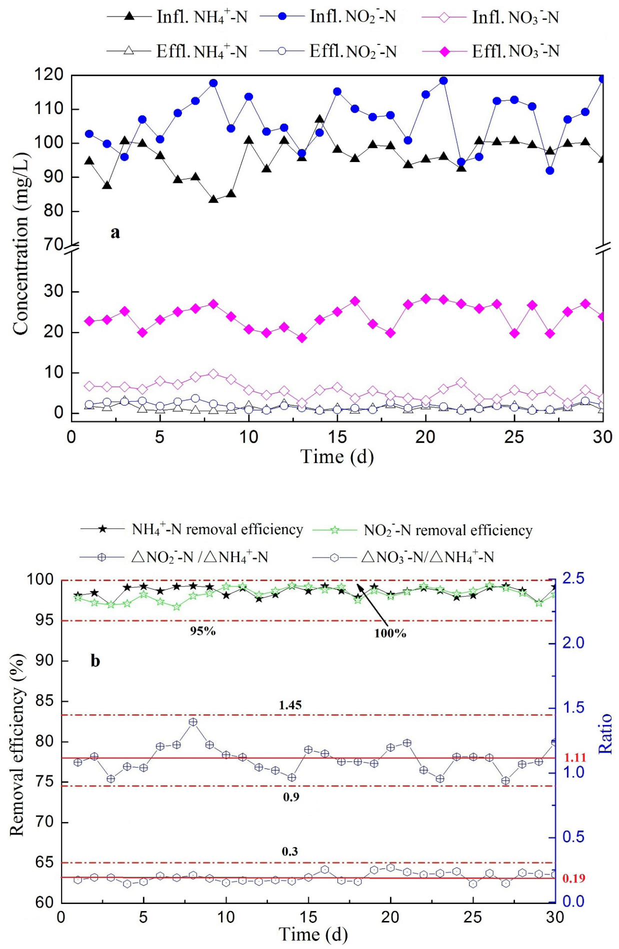

Fig. 11. (a) Profile of nitrogen conversion in UASB reactor (b) Profiles of NO_2^--N/NH_4^+-N and NO_3^--N/ NH_4^+-N ratios in USB reactor.

nitrate of UASB reactor influents were 96.2, 106.7 and 5.6 mg/L, respectively, on average. Ammonium, nitrite and nitrate concentrations of ANAMMOX effluents were 1.4, 1.8 and 24.0 mg/L, respectively. Fig. 11b displays the 98.6% removal efficiency of ammonium and 98.3% removal efficiency of nitrite. ANAMMOX was efficient in removing ammonium and nitrite under the salinity of 16.5 g/L. Fig. 11b shows that the average ratios of ΔNO_2^--N/ΔNH_4^+-N and ΔNO_3^--N/ΔNH_4^+-N were 1.11 and 0.19 (red solid lines), which were closely coordinated with the latest theoretical ratios of 1.146:1 and 0.161:1 modified by Lotti et al. [16]. Fig. 12 shows the influent and effluent pH values. The average influent pH was 7.6 and rose to 8.2 after the reaction. The pH would rise in the UASB reactor, but remain in the optimal range for AnAOB and does not inhibit the process.

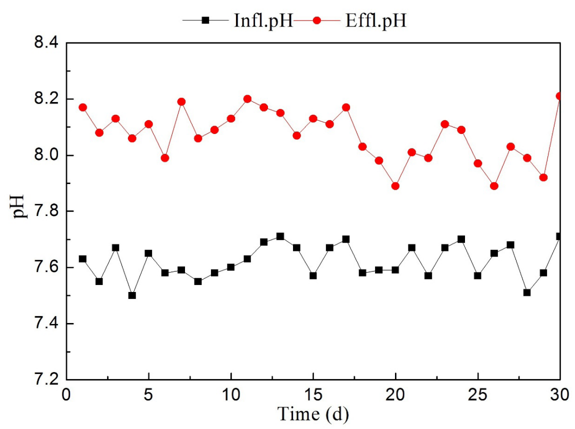

Fig. 12. The pH changes of influent and effluent in UASB reactor.

3.4. Analysis of energy consumption

Compared with the traditional nitrification/denitrification process, the combination system for high-salt mustard wastewater saves energy. Anaerobic digestion process is a biological process that occurs when bacteria break down organic compounds in environments without oxygen [27]. In PN, the oxygen consumption is smaller than complete nitrification by shortened oxidation process. Furthermore, in the subsequent ANAMMOX, no organic was needed. The energy of aeration accounts most energy in wastewater treatment plants; thus, an efficient and economical approach for wastewater treatment is important.

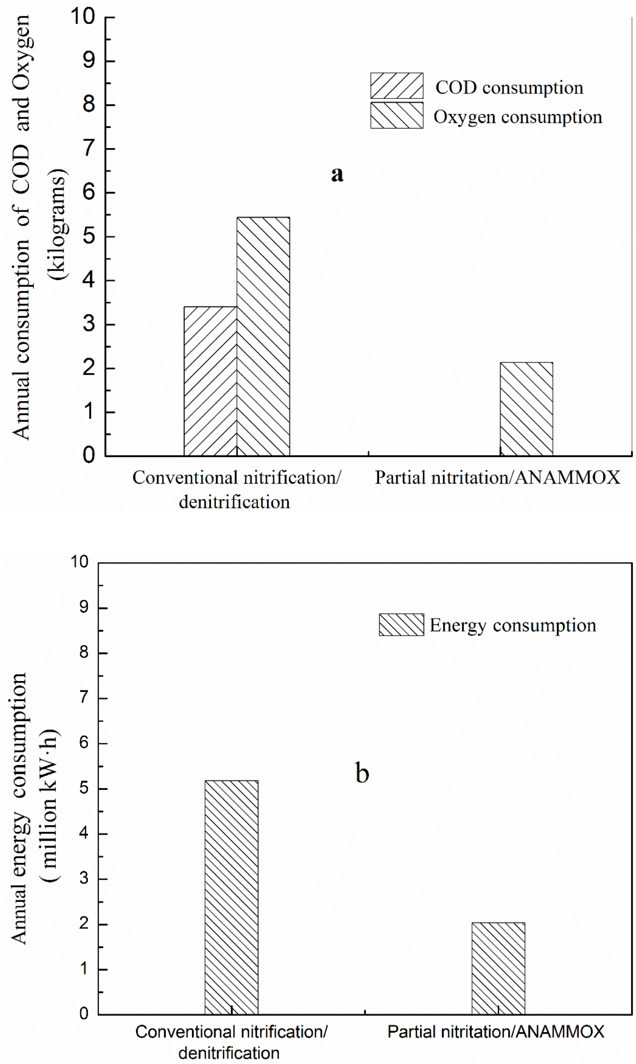

Fig. 13. (a) Annual consumption of COD and oxygen by conventional nitrification/denitrification and PN/ANAMMOX processes (b) Annual energy consumption by conventional nitrification/denitrification and PN/ANAMMOX processes.

A total of 5 × 10^6 m^3 of wastewater is discharged yearly from mustard production in Fuling, Chongqing. Mustard wastewater contains approximately 0.017 mol NH_4^+-N/L, as estimated by TN concentration. As a result, 8.5×10^7 mol NH_4^+-N is produced each year. If the wastewater is treated using conventional nitrification/denitrification process, 3.4 million COD and 5.44 million kg of oxygen will be consumed. Fig. 13a shows the annual consumption of COD and oxygen by conventional nitrification/denitrification and PN/ANAMMOX processes. Compared with conventional nitrification/denitrification, PN/ANAMMOX will consume no organic compounds and only 2.14 million kg of oxygen, with 3.296 million (approximately 60.6%) kg of oxygen saved. The estimation of oxygen savings is based on the ratio of NO_2^--N/NH_4^+-N (1.1:1) from operating data. To date, blasting aeration system is used as an example to analyse the energy consumption. If the single-sided design is applied for aerators in wastewater treatment plants, the oxygen transfer rate will be approximately1.05 kg O_2/kW·h. Based on this data, conventional nitrification/denitrification process and PN/ANAMMOX will consume 5.18 and 2.04 million kW·h electricity, respectively. Fig. 13b shows the annual energy consumption by conventional nitrification/denitrification and PN/ANAMMOX processes; and approximately 3.14 million kW·h electricity will be saved yearly if the combination system is applied.

4. Conclusions

The study has proven that a combined anaerobic, PN and ANAMMOX processes to treat mustard wastewater is feasible. Gradient dilution method and enrichment of salt-tolerant microorganisms played a key role in the start-up phase of ASBBR and SBR. ANAMMOX is sensitive to environmental factors, therefore, raw mustard wastewater is not conducive for the start-up of UASB reactor, but it can adapt very well after combination. Combination of ASBBR, SBR and UASB reactor provided more than 96.7% COD and 87.5% TN removal efficiency in treating high-salt mustard wastewater. Energy consumption analysis showed that the combination process had advantages over the conventional nitrification/denitrification process in treating high-salt wastewater.

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