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Nitrogen removal from wastewater and external waste activated sludge reutilization/reduction by simultaneous sludge fermentation, denitrification and anammox (SFDA)

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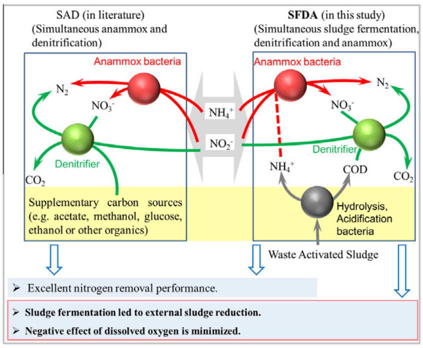
HIGHLIGHTS

- Simultaneous sludge fermentation, denitrification and anammox was demonstrated.
- Long-term stable operation was observed with domestic wastewater as influent.
- Efficient nitrogen removal was achieved by synergy of anammox and denitrification.
- Accidental introduction of air into the system only caused limited negative effect.
- External WAS reutilization promoted nitrogen removal and realized sludge reduction.

GRAPHICAL ABSTRACT



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ABSTRACT

This work demonstrates the feasibility of simultaneous nitrogen removal and external waste activated sludge (WAS) reutilization/reduction by using the synergy of sludge fermentation, denitrification and anammox processes in up-flow reactors (SFDA). Pre-treated domestic wastewater and synthetic wastewater (containing nitrite ~20 mg/L, ammonium ~10 mg/L in both) were fed to 1# and 2# SFDA, respectively. Long-term operation of 1# SFDA was investigated with achieving the peak ammonium removal rate of 0.021 and nitrite removal rate of 0.081 kg N/(m^3 d) as nitrogen loading rate elevated from 0.075 to 0.106 kg N/(m^3 d). Negative effect of dissolved oxygen on anammox or fermentation in the 2# SFDA was demonstrated negligible due to rapid depletion by microorganisms. Furthermore, a "net" sludge reduction of 38.8% was obtained due to sludge decay and organics consumption by denitrification. The SFDA process was expected to potentially be used for nitrogen removal and WAS reutilization/reduction in full-scale application.

1. Introduction

Heterotrophic denitrification, during which nitrate or nitrite is reduced and the principle gaseous end product is molecular nitrogen in the use of organic substrate, is by far the most prevalent and concise strategy in wastewater treatment plants (WWTPs) to achieve biological nitrogen removal. When carbon sources in raw wastewater are insufficient, chemical organic compounds, such as methanol, acetate or glucose, are added to improve denitrification efficiency in most cases (Her and Huang, 1995). However, that

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is a huge expense for WWTPs, contributing up to 70% of the total operating and maintenance costs (Elefsiniotis and Li, 2006).

Waste activated sludge (WAS), the major byproduct of wastewater treatment produced during biological transformation processes after secondary clarification, is an inexpensive available carbon source. Peccia and Westerhoff (2015) proposed that the traditional regulatory-driven treatment-based approach on sludge management must be converted to a resource recovery-based enterprise, that means organics and nitrogen compounds in WAS are utmost expected to be converted to the end products of gaseous materials, such as carbon dioxide and dinitrogen that will take part in carbon- and nitrogen-cycles again. In this sense, anaerobic sludge fermentation is an appropriate way, through which autotrophic or heterotrophic biomass decay and cell lyse under anaerobic condition, resulting in the release of inorganic or organic carbon sources. Proteins and carbohydrates are hydrolyzed and fermented to organic acids during fermentation of WAS (Pratt et al., 2012), rendering electron and energy for denitrification process in wastewater treatment. At the same time, the decay of WAS reduces the yield and addresses the sludge disposal problems to an extent (Zhou et al., 2015). However, one important trade-off is to note that relying on denitrification-only process to consume organic substrate produced from anaerobic sludge fermentation will not remove ammonium released from WAS (Chen et al., 2007; Wu et al., 2014), thus additional technologies are required.

Nitrogen removal from wastewater using coexistence of heterotrophic denitrification and anammox microorganisms has been investigated in laboratory studies within the last decade. The anammox process is an energy-efficient nitrogen removal process, but requires a specific nitrite to ammonium ratio (Kuenen, 2008). Alternatively, the simultaneous anammox and heterotrophic denitrification (SAD) process, fed with ammonium and nitrate in a sequential batch reactor, removed nitrogen efficiently at different C/N ratios (Takekawa et al., 2014). Anammox contributed predominantly to total nitrogen removal (80–100%) under low C/N ratios of 0.5–1.0, but transient nitrite accumulation might occur at high concentrations of enhanced nitrate reduction. However, when a given amounts of nitrite and ammonium were supplied in the influent, Ahn et al. (2004) demonstrated that partial denitrification and anammox could be performed successfully, and the anammox was influenced less by the degree of partial denitrification. Around 47–57% of ammonium and 78–83% of nitrite was removed via anammox process, contributing to 65–71% of total nitrogen removal.

In spite of these above successful attempts, several issues still require to be addressed before the SAD process being applied for full-scale wastewater treatment. First, due to insufficient readily organics for heterotrophic denitrification after aerobic nitrification, external carbon sources are required to supplement. Alternative carbon sources rich in fatty acids could be produced by disintegration or fermentation of sludge and supplied for in-situ denitrification, by which the simultaneous sludge fermentation and denitrification is established therefore (Wu et al., 2014; Zhang et al., 2013). A previous study demonstrated that a most reduction of nitrite to dinitrogen was achieved by adding nitrite to sludge fermentation systems and WAS acidification was improved in turn (Wang et al., 2014). Second, the slow growth of anammox microorganisms and the competition for nitrite between anammox bacteria and denitrifiers might determine a low contribution to nitrogen removal by anammox process in comparison with denitrification. However, whether it should be counted as a challenge depend on what is expected of anammox. Just like its function in the case of nitrogen removal from sludge digester liquids (Joss et al., 2009; Schaubroeck et al., 2015), anammox is desired to eliminate ammonium released from sludge fermentation at least.

The aim of this study is to investigate the performance of simultaneous ammonium and nitrite removal via the synergy of anammox and heterotrophic denitrification using external WAS as a carbon source. To this end, a simultaneous sludge fermentation, denitrification and anammox process (SFDA) was intermittently added with WAS and continuously fed with nitrite and ammonium in the liquid from a pre-partial nitritation reactor. Concentrations of nitrite and ammonium were measured to assess the performance of the SFDA. Batch tests with various nitrogenous composition ($NO_2^- + NH_4^+$, NO_2^- only, NO_3^- only) were performed in the middle of the operation to verify the reactions. A possible situation for the penetration of dissolved oxygen (DO) into the SFDA reactor was also evaluated.

2. Materials and methods

2.1. Bioreactors set-up and operation

Two lab-scale up-flow sludge bed reactors were used in this study (Fig. 1), both of which had an internal diameter of 6 cm and a height of 120 cm on the bottom and an internal diameter of 14 cm and a height of 32 cm on the top. Moderate mixing of the reactors was performed by peristaltic pumps to prevent gas built-up and channel formation. Moreover, they were covered with black sponge to avoid the growth of phototrophic organisms. One was selected as an experiment reactor (termed as 1# SFDA), and the other was used as a control (termed as 2# SFDA). Initially, the control reactor was operated in an identical mode to the experiment reactor for around 50 d to establish a steady state, during which both were fed with the discharge from a pre-Partial Nitritation sequencing batch reactor (PN SBR) including ammonium and nitrite (Details on PN reactor operation was shown in Supplementary Materials). Afterward, synthetic wastewater simulating similar concentrations of ammonium and nitrite (Further described in the following paragraph) was fed to the control reactor. During the entire experimental operation, 0.15 L/d (~0.85 g/d solid) of external WAS collected from a pilot scale SBR was transported into 1# and 2# SFDA reactors, respectively. Main characteristics of the concentrated external WAS were as follows: total suspended solids (TSS) 7.7 ± 1.2 g/L, volatile suspended solids (VSS) 6.7 ± 1.2 g/L, soluble chemical oxygen demand (SCOD) 107.0 ± 21.2 mg/L and NH_4^+–N 65.9 ± 17.4 mg/L. Both reactors were operated continuously at ambient temperature (16–29 °C).

Both SFDA reactors were operated for approximately 4 months, during which the operation conditions of the control reactor remained the same with the hydraulic retention time (HRT) being 18 h, as is detailed in Table 1. The synthetic wastewater was comprised of various components (modified from Du et al. (2014)), with the total COD concentrations being lower than 10 mg/L to eliminate the dependency of denitrification on external organics. The detailed composition was (per liter): 38.2 mg NH_4Cl (10 mg NH_4^+–N), 98.6 mg $NaNO_2$ (20 mg NO_2^-–N), 0.03 mg KH_2PO_4, 0.12 mg $CaCl_2{\cdot}2H_2O$, 0.5 mg $KHCO_3$, 0.14 mg $MgSO_4{\cdot}7H_2O$, 20 mg EDTA, 9.1 mg $FeSO_4{\cdot}7H2O$, 0.014 mg H_3BO_3, 0.43 mg $ZnSO_4{\cdot}7H_2O$, 0.24 mg $CoCl_2{\cdot}6H_2O$, 0.99 mg $MnCl_2{\cdot}4H_2O$, 0.25 mg $CuSO_4{\cdot}5H_2O$, 0.19 mg $NiCl_2{\cdot}6H_2O$, 0.22 mg $NaMoO_4{\cdot}2H_2O$.

The PN reactor was fed with domestic wastewater as inflow (collected from the residential area of Beijing University of Technology (Beijing, China)). The compositions of domestic wastewater were as follows: NH_4^+–N 61.7 ± 9.0 mg/L, COD 165.6 ± 40.4 mg/L, NO_2^-–N and NO_3^-–N undetected. The nitrogen and COD removal performance of the PN reactor was shown in Fig. 2 and the discharge from PN reactor was fed into the SFDA as influent. The operation of experiment SFDA reactor was divided into three phases.