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SHORT RESEARCH AND DISCUSSION ARTICLE

Effect of magnetic powder on denitrification using the sludge alkaline fermentation liquid as a carbon source

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Abstract

This work evaluates the impact of the different concentrations of Fe_3O_4 on nitrate removal and organic matters utilization in the sequencing batch reactors (SBRs) using the sludge alkaline digestion supernatant as external sludge carbon source. Results indicated that the optimal concentration of Fe_3O_4 was 1 g/L for enhancing denitrification with NO_3^--N removal efficiency of 93.13% (up to a 11.93% increase) and without NO_2^--N accumulation after 18 days. The changes of soluble chemical oxygen demand (SCOD), protein, and carbohydrate during denitrification process were analyzed to gauge the utilization of sludge fermentation products by denitrifiers. The SCOD was consumed for organisms involved in NO_3^--N removal and the Fe_3O_4 could promote the utilization of carbohydrate better than protein by denitrifiers during denitrification process. Denitrification rate (V_{DN}) and the nitrate-to-nitrite transformation ratio (NTR), as the kinetics parameters, were also investigated in different concentrations of Fe_3O_4.

Keywords Nitrate removal · Fe_3O_4 · Anaerobic fermentation · Carbon source · Waste sludge · Sequencing batch reactors

Abbreviations

WWTPs	Wastewater treatment plants
WS	Waste sludge
MF	Magnetic field
SBRs	Sequencing batch reactors
HRT	Hydraulic retention time
SRT	Sludge retention time
SAFL	Sludge alkaline fermentation liquid
Fe_3O_4	Magnetic powder
V_{DN}	Denitrification rate

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NTR	The transformation ratio from nitrate to nitrite
A^2O	Anaerobic-anoxic-oxic
MLVSS	Mixed liquor volatile suspended solid
TSS	Total suspended solid
VSS	Volatile suspended solid
NO_3^--N	Nitrate
NO_2^--N	Nitrite
NH_4^+-N	Ammonia nitrogen
TN	Total nitrogen
SPSS	Statistical package for social sciences

Introduction

Biological nitrogen removal via heterotrophic denitrification is a promising technology to convert NO_3^--N to harmless N_2 carried out by denitrifying microbes which can use organic carbon as electron donors under anoxic conditions (Rezvani et al. 2019). However, the efficiency of denitrification is restricted by the insufficient external organic carbon in wastewater treatment plants (WWTPs) (Si et al. 2018; Wu et al. 2018). Thus, extensive carbon substrates have been usually chosen to sustain denitrification, such as methanol, ethanol, glucose, and acetate (Zhang et al. 2016). Nevertheless, the exploitation of external carbon source lead to increased financial costs and a large amount of sludge production (Xue et al. 2018). Thus, choosing an alternative cost-effective and sustainable external carbon source have been highlighted among the priorities of the WWTPs (Kim et al. 2016).

Large quantities of waste sludge (WS) are generated in biological treatment processes, which increases the cost of the total wastewater treatment (Zhang et al. 2017). At the same time, excessive WS involves large quantities of organic matters, which needs for a reliable and economically viable approach of sludge management (Li et al. 2013). Among some methods, such as bio-surfactant treatment (Guan et al. 2017), ultrasonic treatment (Zielewicz 2016), ozone treatment (Fall et al. 2018), thermal treatment (Kumi et al. 2016), acid/alkaline treatment (Wang et al. 2017; Wu et al. 2017), and combined treatment (Ke et al. 2018), anaerobic alkaline fermentation (pH > 9) has been proved to be an effective way by shortening the time of hydrolysis and inhibiting methanogens activity for volatile fatty acids (VFAs) accumulation (Wang et al. 2017). Consequently, some researchers have verified that the cumulation of VFAs during WS alkaline fermentation was remarkably improved compared with other conditions (Li et al. 2018b). Nowadays, sludge fermentation liquid has been frequently exploited to produce biodegradable carbon source for denitrification instead of additional supply of organic chemicals to decrease the cost of wastewater treatment, which might be able to achieve stable nitrogen removal and efficient excess sludge reutilization simultaneously (Zheng et al. 2018).

Due to positive magnetic bio-effect and eco-friendly nature, some magnetic materials have been used to improve reactor performance in the treatment of municipal wastewater. In view of their own performance advantages of the magnetic materials, such as inert, biocompatible, and the high surface-to-volume ratio, the activated sludge added Fe_3O_4 facilitates the removal of contaminants and furthermore, will not cause detrimental effects on performance (Liu et al. 2018b; Semblante et al. 2013). Fe_3O_4 can not only influence on the proliferation of microorganisms by inducing of magnetic field (MF) and Fe ion but also promote nutrient removal capability compared with without Fe_3O_4 (Liu et al. 2018a; Ren et al. 2018b). Otherwise, reactors Fe_3O_4 addition could improve the sludge sedimentation efficiency by strengthening flocculation, and MF could also magnetize the Fe-compounds in reactors (Ren et al. 2018a).

Nevertheless, few studies reported the effect of the different concentrations of Fe_3O_4 on nitrogen compounds removal using the sludge alkaline fermentation liquid (SAFL) and the fate of the organic matters correspondingly during biological nitrogen removal process. The main objective of the present study was to compare the denitrification performance between magnetic and non-magnetic SBRs and to reveal the optimum magnetic powder concentration enhancing bio-effect on denitrification process. This study presented a novel strategy to assess the effect of the different concentrations of Fe_3O_4 on NO_3^--N, NO_2^--N, NH_4^+-N, and TN concentrations, using the SAFL as carbon source. The detailed characterization variation of the organic compounds of SCOD, protein, and carbohydrate together with biological nitrogen removal were also determined. Dynamics analyses (V_{DN} and NTR) were introduced to investigate the variation of carbon source components during denitrification, which could improve understanding of the denitrification process with SAFL as carbon source.

Materials and methods

Magnetic powder and WS

Magnetic powder with the particle size of 15 μm was purchased from Tianjin Dingshengxin Chemical Industry Co., Ltd. (Tianjin, China).

The seed sludge and sludge used for making SAFL collected from the sludge secondary sedimentation tank in a full-scale Qingdao's Tuandao WWTP (China) were selected for this work. The nitrate removal of this WWTP is an anaerobic-anoxic-oxic (A^2O) process, and the hydraulic retention time (HRT) and sludge retention time (SRT) are 19 h and 11.5 d, respectively. In order to remove coarse matter, sludge was filtered through a 2.0 mm screen prior to use, and the concentrated sludge was stored in 4 °C refrigerator for 24 h before used.

Synthetic wastewater

Each bottle prepared with synthetic wastewater was prepared as follows: SCOD, 480 mg/L; NO_3^--N (KNO_3), 60 mg/L; PO_4^{-3} (KH_2PO_4), 3 mg/L; $NaHCO_3$, 200 mg/L, and 1 mL/L trace-element solution which contained: $MgSO_4 \cdot 7H_2O$, 30 g/L; H_3BO_3, 0.05 g/L; $FeSO_4 \cdot 7H_2O$, 17.2 g/L; $ZnCl_2$, 6.10 g/L; $CaCl_2 \cdot 2H_2O$, 7.5 g/L; $CuSO_4 \cdot 5H_2O$, 0.22 g/L; $MnCl_2 \cdot 4H_2O$, 0.5 g/L; $CoCl_2 \cdot 6H_2O$, 0.50 g/L; $NiCl_2 \cdot 6H_2O$, 0.01 g/L.

Experimental methods

Preparation of the SAFL

SAFL as electron donor for denitrification was added in reactors. A commercial vessel (5 L) was run at a mesophilic temperature of 35 ± 2 °C for fermentation process. The pH for the alkaline anaerobic fermentation was subjected to 10 with 2 mol/L NaOH solution or 2 mol/L HCl solution. The mixture was fermented for 24 h at 35 °C at 60 rpm by a motor agitator. Then, the mixture was centrifugated at 4000 rpm for 15 min to remove large particle size solids, and the supernatant was filtered by a 0.45 μm cellulose acetate membrane to collect the SAFL. The supernatant would be stored at 4 °C before used. The characteristics of SAFL were as follows: SCOD 2587.1 ± 129.5 mg/L, VFAs 881.7 ± 44.1 mg/L, soluble protein 243.5 ± 27.2 mg/L, and soluble carbohydrate 117.0 ± 15.8 mg/L, respectively.

Cultivation of denitrifying sludge

In order to cultivate the denitrifying sludge, the identical laboratory-scale SBR was equipped with influent pump and effluent pump, which was mechanically stirred for the complete mixing during the reaction. This SBR was conducted in ambient temperature about 20 ± 1 °C and operated with a cycle period of 12 h to maintain HRT of 24 h. CH_3COONa was conventionally considered as an ideal carbon source for the cultivation of denitrifying sludge, favoring of the metabolic pathway of nitrate. Thus, the influent SCOD which was provided of the CH_3COONa in this work was set at about 480 mg/L, and $NaNO_3$ about 60 mg/L was the sole nitrogen source, resulting in a SCOD to NO_3^--N ratio of 8.0. Namely, 2 cycles were run each day which contained feeding (without mixing), 11 h anoxic, 40 min settling, 3 min decanting, and 17 min idle periods. Effluents were discharged out of the reactors at half of the working height after the setting period, thus making the exchange ratio of 50%. Then, the fresh synthetic wastewater replaced with an equal volume in the next cycle. When the NO_3^--N removal rate was above 98.0% stably in the effluent, it was considered to be successful in denitrifying sludge cultivation. The characteristics of cultured denitrifying sludge were shown in Table 1.

SBRs operation and sampling

Six sealed conical flasks (250 mL) with the concentrations of Fe_3O_4 of 0, 0.5, 1.0, 1.5, 2.0, and 2.5 g/L were employed to characterize the effect of Fe_3O_4 on denitrification performance, respectively. Those SBRs were conducted in ambient temperature about 20 ± 1 °C. The denitrifying sludge first added into six reactors to maintain the mixed liquor volatile suspended solid (MLVSS) was 400 mg/L, and the sludge age was approximately 18 days. In synthetic wastewater, SAFL instead of sodium acetate as electron donor was added to the reactor. Then, the reactor was covered with the sealing film after each reactor was flushed with high-purity N_2 for 5 min to maintain anoxic condition. The effluent samples were first centrifuged at 4000 rpm for 10 min, then filtered with 0.45 μm syringe filters. Under identical condition, the measurements were conducted in triplicate for getting reliable results.

Analytical methods

The TSS (total suspended solid), VSS (volatile suspended solid), and NO_3^--N, NO_2^--N, and NH_4^+-N were described previously (Guo et al. 2018; Shao et al. 2019). TN (total nitrogen) was calculated by the sum of NO_3^--N, NO_2^-N, and NH_4^+-N. The TCOD (total chemical oxygen demand) and SCOD (soluble chemical oxygen demand) were determined by potassium dichromate method. pH was measured using a pH meter (Sension1, HACH, USA). Soluble carbohydrate was determined in the phenol-sulfuric assay, and the protein was determined in the Lowry-Folin assay (Zhang et al. 2017). VFAs were analyzed by a gas chromatograph (GC2010, Shimadzu, Japan) equipped with an a flame ionization autoinjector (DB-FFAP, inner diameter of 0.25 mm and length of 30 m) (Sun et al. 2016). Statistically analyzed data for the effects of the different concentrations of Fe_3O_4 on NO_3^--N removal and V_{DN} by using SPSS 20.0 software evaluate the significance of data. Significance was established at $p < 0.05$

Table 1 Characteristics of cultured denitrifying sludge

pH*	TSS* (mg/L)	VSS* (mg/L)	TCOD* (mg/L)	SCOD* (mg/L)	Proteins* (mg/L)	Carbohydrates* (mg/L)
7.0 ± 0.4	921.3 ± 50.1	448.2 ± 20.3	9204.3 ± 92.1	333.1 ± 3.4	17.4 ± 0.9	15.1 ± 0.2

* The results were conducted in triplicate and expressed as mean ± standard deviation

(Song et al. 2019). Office Excel 2016 (Microsoft, USA) was performed to analyze data and the graphs were plotted using Origin 8.5 for data visualization.

Calculation of denitrification parameters

The NO_x-N removal curve with reaction time could be obtained based on $NO_x\text{-N} = NO_3^-\text{-N} + 0.6 \times NO_2^-\text{-N}$ (Zhang et al. 2016). The equation for the denitrification rate (V_{DN}: mg NO_x-N/gVSS·h) is given by the following equation (Eq. (1)) based on the NO_x-N removal curve (Guo et al. 2018; Zhang et al. 2016):

$$V_{DN} = (N_{\text{initial}} - N_{\text{end}})/(VSS \times t) \quad (1)$$

N_{initial} (mg/L): the initial NO_x-N concentration; N_{end} (mg/L): the tapping point of the NO_x-N concentration; VSS (g/L): the concentration of volatile suspended solids; t (h): the reaction time involving the reaction.

The NTR is calculated using Eq. (2) (Du et al. 2016).

$$NTR = (NO_2^-\text{-}N_t - NO_2^-\text{-}N_{in})/(NO_3^-\text{-}N_{in} - NO_3^-\text{-}N_t) \times 100\% \quad (2)$$

NTR (%): the transformation ratio from NO_3^--N to NO_2^--N; $NO_2^-\text{-}N_{in}$ (mg/L): the influent of NO_2^--N concentration; $NO_3^-\text{-}N_{in}$ (mg/L): the influent of NO_3^--N concentration; $NO_2^-\text{-}N_t$ (mg/L): the tapping point of NO_2^--N concentration; $NO_3^-\text{-}N_t$ (mg/L): the tapping point of NO_3^--N concentration.

Results and discussion

Effect of Fe_3O_4 on denitrification performance

At different concentrations of Fe_3O_4, the effluent variations of NO_3^--N, NO_2^--N, NH_4^+-N, and TN during denitrification with the SAFL as carbon source were shown in Fig. 1. At stage 1, the NO_3^--N removal efficiencies were 28.40, 30.70, 37.03, 31.99, 32.12, and 24.42% at 0–2.5 g/L Fe_3O_4, respectively, which implied that the effect of Fe_3O_4 on the removal of NO_3^--N was similar at this stage. Large quantities of complicated and non-biodegradable organic compounds released from the alkali treated sludge, which included building blocks, the high molecular weight protein and high molecular weight polysaccharide (Cao et al. 2019). Thus, the denitrification bacteria did not accommodate to the new sludge carbon source at the start-up period. The NO_2^--N, as the intermediate product of denitrification, accumulated to 11.72, 12.07, 14.04, 11.94, 10.29, and 12.83 mg/L at 4 d, which implied that the NO_3^--N was partly converted to NO_2^--N resulting in incomplete denitrification in such short time. Meanwhile, the higher NO_2^--N accumulation was achieved in 0.5–2.5 g/L Fe_3O_4 probably due to the activity of nitrate-reducing bacteria enhanced by magnetic bio-effect (Liu et al. 2018b).

At stage 2, NO_3^--N removal efficiencies were largely improved than those of stage 1, which were 68.53, 84.64, 87.53, 73.56, 73.99, and 75.70%, respectively. Especially, the NO_3^--N removal of SBRs at 0.5–1 g/L Fe_3O_4 were significantly higher than other Fe_3O_4 dosages ($p < 0.05$) (Online Resource Table S1). It implied that the denitrification bacteria adapted to the new environment of fermentation products gradually. Moreover, all maximum NO_2^--N accumulation could be observed nearly corresponding to the turning point of NO_3^--N reduction. More NO_2^--N accumulation resulted from higher NO_3^--N removal amount and began to reduce after completely depleted of NO_3^--N. The activity of NO_3^--N reductase was higher than NO_2^--N reductase due to the competition of the matrix electrons between NO_3^--N reductase and NO_2^--N reductase (Guo et al. 2017).

At stage 3, the removal efficiencies of NO_3^--N reached up to 93.13 (with 1 g/L Fe_3O_4) and 81.20% (without Fe_3O_4), respectively. Besides, the p value between Fe_3O_4 of 0 and 1 g/L was less than 0.05 for NO_3^--N removal efficiency (Online Resource Table S1). Adding 1 g/L Fe_3O_4 in SBRs could significantly promote the removal of NO_3^--N. At the same time, there was little NO_2^--N or NH_4^+-N (below 0.7, 10 mg/L, respectively) in the effluent. It was implied that the denitrifiers had completely accommodated the new sludge carbon source after 18 days of cultivation.

The NH_4^+-N (Fig. 1c) concentration increased about 45 mg/L from 1d to 6d in all reactors. The degradation of complex nitrogen-containing macromolecular compounds, particularly protein and DNA, resulted in the NH_4^+-N release during the anoxic environment (Miron et al. 2000), which was independent of denitrification. It was found that the effluent NH_4^+-N of all SBRs added Fe_3O_4 were higher than that without Fe_3O_4 in stage 2. It indicated that Fe_3O_4 could significantly promote the fermentation of proteinaceous organic matter. Although the NH_4^+-N had the inhibitory effect on denitrification (Rikmann et al. 2017), the NH_4^+-N decreased to 5–8 mg/L of all Fe_3O_4 dosages after 18 days of cultivation. Assimilatory denitrification led to formation of NH_4^+-N for cell synthesis when NO_3^--N was the only nitrogen source (Plug et al. 2015; Sun et al. 2016). However, the MF generated by Fe_3O_4 did not contribute to NH_4^+-N removal (Kriklavova et al. 2014; Zhao et al. 2018). Due to the fact that inhibition caused by NH_4^+-N was reversible, the physical properties of the SBRs were not substantially affected by the presence of NH_4^+-N (Fernandez et al. 2012).

The variation of TN during denitrification process was shown in Fig. 1d. At 0–2.0 g/L Fe_3O_4, the effluent TN concentrations were 16.46, 14.74, 14.19, 15.17, and 12.95 mg/L with the removal efficiencies of 75.10, 79.41, 79.09, 76.51, and 78.11%, respectively. It illustrated that denitrifying microorganisms acclimatization and nutrient removal processes under magnetic field were stimulated. The magnetic field induced by Fe_3O_4 enhanced the removal of nitrogen

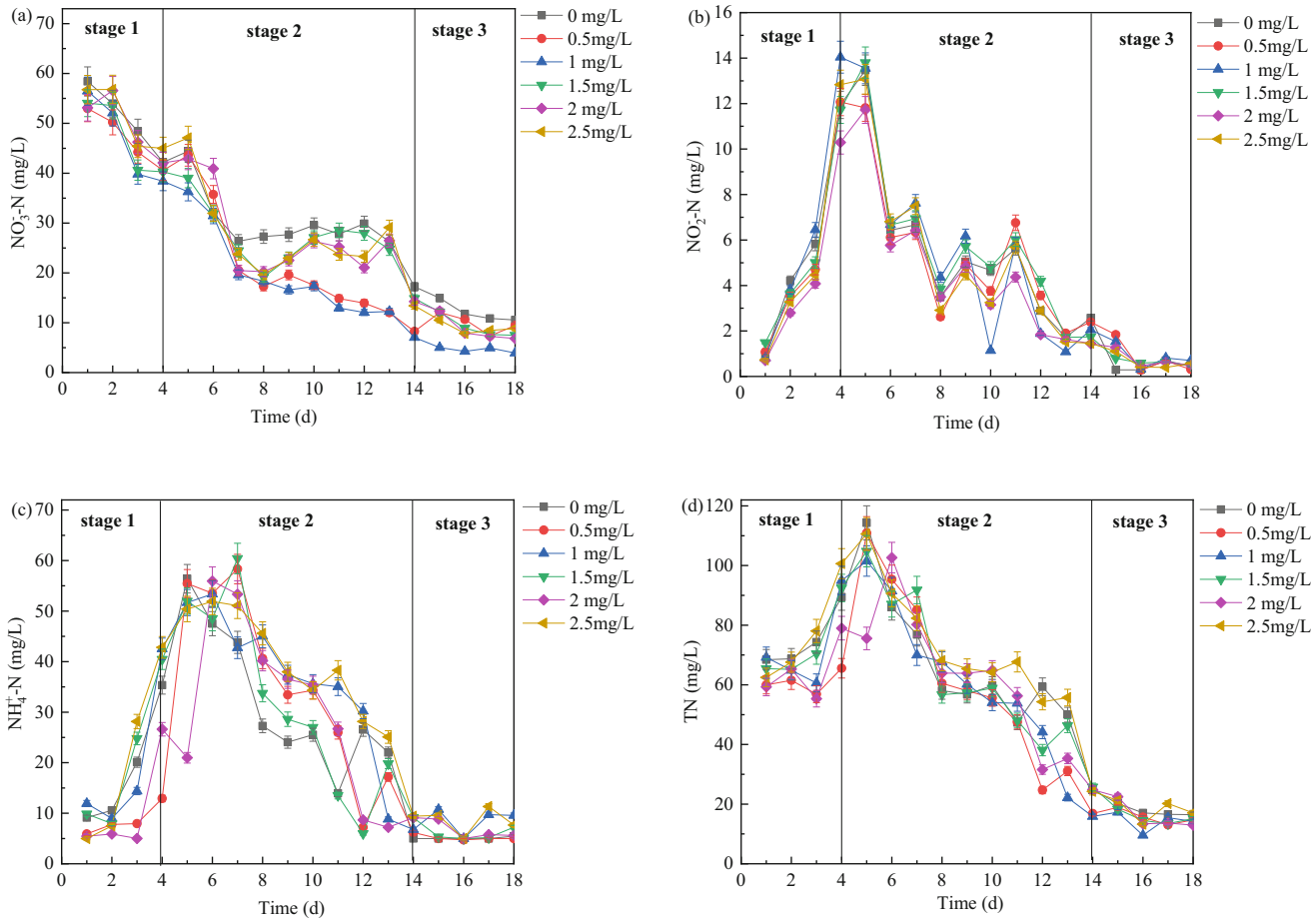

Fig. 1 Variations of effluent NO_3^--N, NO_2^--N, NH_4^+-N, and TN during denitrification process using SAFL as carbon source at different concentrations of Fe_3O_4

compounds by increasing their contact opportunities with denitrifying bacterias, resulting in the higher denitrification efficiencies (Ji et al. 2010). However, slight increase was noticed for effluent TN (17.07 mg/L) with further increasing the concentration of Fe_3O_4 to 2.5 g/L. It showed that Fe_3O_4 could influence living organisms to stimulate the biodegradation of wastewater, whereas high concentration of Fe_3O_4 could occur to toxicity to denitrifying microorganisms (Li et al. 2018a).

Figure 2 showed a typical variation profile of V_{DN} and NTR along the denitrification process using SAFL as carbon source at different concentrations of Fe_3O_4. The maximized denitrification rate (V_{DN}) at 0.5–2.5 g/L Fe_3O_4 (10.58, 11.05, 9.89, 9.55, 10.21 mg NO_x-N/gVSS·h, respectively) were higher than 0 g/L Fe_3O_4 (9.48 mg NO_x-N/gVSS·h), especially at 1 g/L Fe_3O_4 ($p < 0.05$) (Online Resource Table S1). It indicated that bioactivity of denitrifying bacteria and nutrient removal processes under MF were strengthened (Ji et al. 2010;

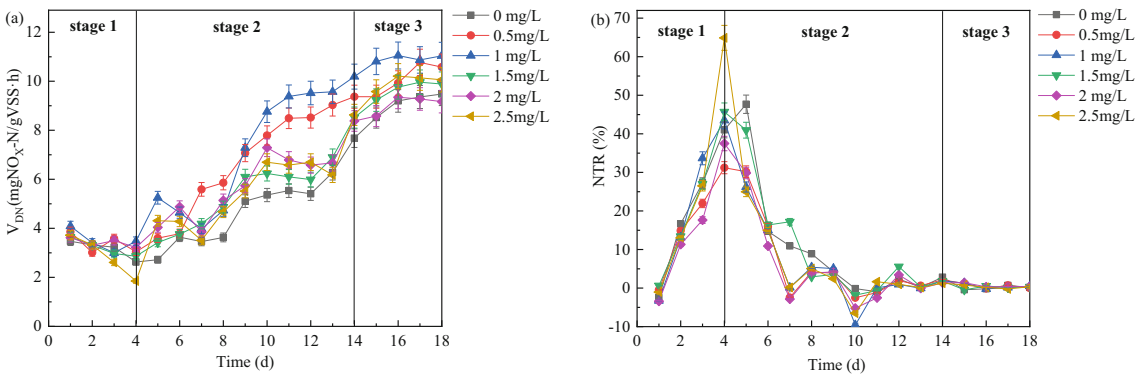

Fig. 2 Variations of V_{DN} and NTR during denitrification process using SAFL as carbon source at different concentrations of Fe_3O_4

Liu et al. 2018b), so the denitrifying bacteria could get more electrons from sludge fermentation products, resulting in a higher denitrification efficiency of reactors. Although the V_{DN} at 2.5 g/L Fe_3O_4 was higher than without Fe_3O_4, the removal rate of TN was lower than that without Fe_3O_4. High concentration of Fe_3O_4 had a positive impact on the catabolic enzyme activity of sludge bacteria (Wang et al. 2016) but negatively influenced the bacterial growth during wastewater treatment (Filipic et al. 2012). Additionally, the NTR at the NO_2^--N peak value were 47.68, 31.22, 43.48, 40.95, 29.84, and 24.97%, respectively, at 0–2.5 g/L Fe_3O_4. It indicated that only a small fraction of the removed NO_3^--N was converted to NO_2^--N. Furthermore, the NO_2^--N accumulation peak at 0.5–2.5 g/L Fe_3O_4 (4d) occurred earlier than 0 g/L Fe_3O_4 (5d). Fast NO_3^--N conversion rate under MF led to the fast NO_2^--N generation rate (Liu et al. 2018a). Under consideration of nitrogen removal efficiency, V_{DN} and NTR, 1 g/L Fe_3O_4 was the optimal concentration.

Effect of Fe_3O_4 on organic matters utilization

The SCOD, protein, and carbohydrate concentration profiles during the denitrification at different concentrations of Fe_3O_4 using SAFL as carbon source were shown in Fig. 3. At stage 1, the effluent SCOD showed different trends with the utilization efficiencies of 14.89, 17.98, 8.77, 9.49, 7.06, and 14.46% at 0–2.5 g/L Fe_3O_4, respectively. This illustrated that the denitrification bacteria did not adapt to the new sludge fermentation products, so the utilization of SCOD by denitrifying bacterias was unstable. However, the carbohydrate showed a trend of rapid increase at stage 1 and then reached peak value in all SBRs due to the hydrolysis of sludge existed in the anaerobic or anoxic environment (Zhang et al. 2017). Oppositely, the protein dropped sharply at stage 1 at 0–2.5 g/L Fe_3O_4. Anaerobic fermentation of protein resulted in the enhancement of NH_4^+-N in SBR (Wang et al. 2019).

At stage 2, the utilization efficiencies of SCOD were 56.79, 50.56, 61.73, 68.09, 51.04, and 61.54% at 0–2.5 g/L Fe_3O_4, respectively. The SCOD was consumed rapidly for organisms involved in NO_3^--N removal in the stage 2. However, the utilization efficiency of carbohydrate and protein fluctuated during the stage 2. This was due to that key functional bacteria survived and functioned in SBRs such as hydrolysis/acidification bacteria and denitrifiers (Zhang et al. 2018). Microbial acidification released amount of SCOD to supply carbon for organisms involved in denitrification, and after that sludge fermentation was further stimulated by the organics-driven consumption (Wang et al. 2019). Moreover, the amount of protein accumulation were higher at 0.5–2.5 g/L Fe_3O_4 compared with 0 g/L Fe_3O_4, especially 1 g/L (Online Resource Table S2). The magnetic function of the Fe_3O_4 enhanced the activity of the hydrolase secreted by microorganism (Lebkowska et al. 2011). Furthermore, denitrifying

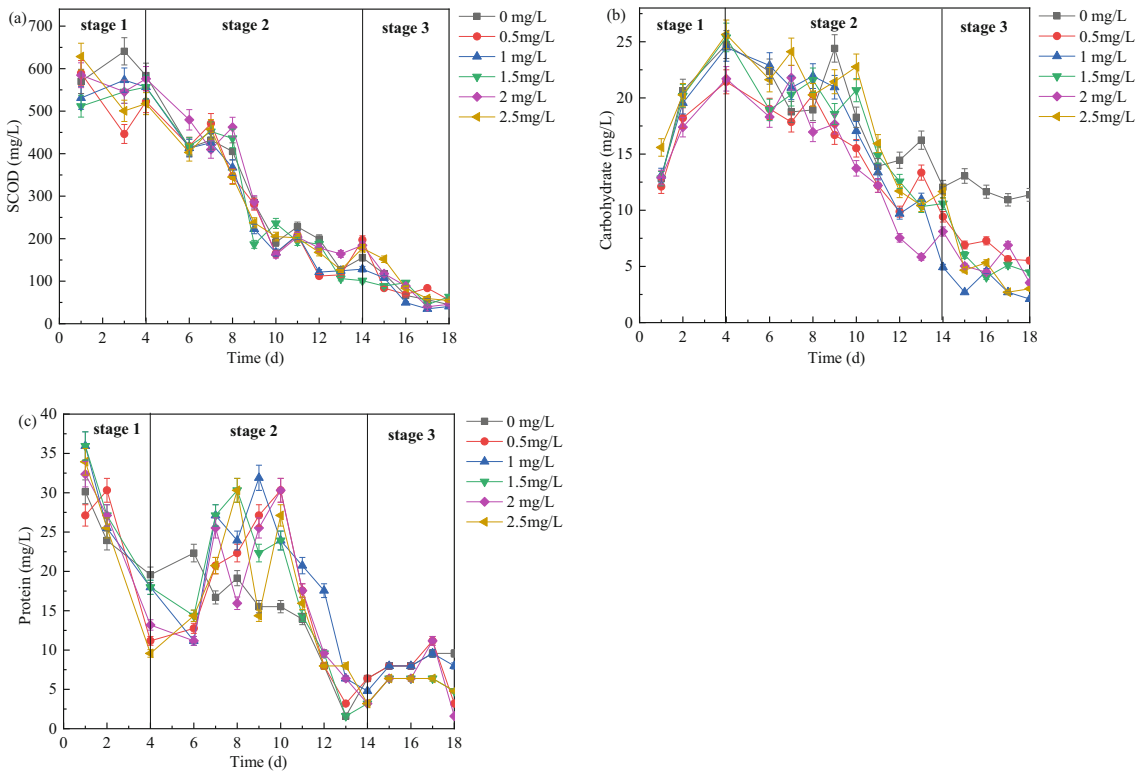

Fig. 3 Variations of effluent SCOD, carbohydrate and protein during denitrification process using SAFL as carbon source at different concentrations of Fe_3O_4

microorganism could not use protein as carbon source or electron donor due to their high molecular weight and complex structure (Yuan et al. 2019).

At stage 3, the effluent SCOD was influenced little by Fe_3O_4 addition. The effluent SCOD concentration were 44.76, 55.85, 40.72, 63.39, 45.58, and 54.49 mg/L with the utilization efficiencies of 84.45, 83.87, 86.09, 82.67, 84.43, and 82.55% at 0–2.5 g/L Fe_3O_4, respectively (18d). The SCOD utilization efficiency was consistent with NO_3^--N reduction. At 0–2.5 g/L Fe_3O_4, the effluent carbohydrate were 11.37, 5.52, 2.10, 4.46, 3.55, and 3.01 mg/L, and effluent protein were 9.57, 3.19, 7.98, 4.79, 1.60, and 4.79 mg/L, respectively. The lower effluent carbohydrate and protein Fe_3O_4 addition were due to positively magnetic bio-effect capability (Liu et al. 2018b). Furthermore, it also found that the Fe_3O_4 could promote the utilization of carbohydrate better than protein by denitrifiers significantly during stage 3 ($p < 0.05$), especially at 1 g/L (Online Resource Table S2). Hydrophilic carbohydrate had the lower molecular weight matters than hydrophobic proteins (Ma et al. 2013), so the MF was more responsive to carbohydrate. Thus, the optimum Fe_3O_4 concentration of 1 g/L could stimulate organic matters utilization via the denitrification process.

Conclusions

This study has successfully investigated the effect of the different concentrations of Fe_3O_4 on nitrate removal and organic matters utilization using the SAFL as carbon source. The optimal concentration of Fe_3O_4 for complete denitrification is 1 g/L with the maximized denitrification rate (V_{DN}) of 11.05 mg NO_x-N/gVSS·h after 18 days of cultivation. By means of denitrification parameters analysis, adding Fe_3O_4 can accelerate the conversion of NO_3^--N to NO_2^--N. The maximal NO_3^--N removal efficiency of 93.13% and the effluent SCOD of 40.72 mg/L are achieved at optimal concentration of Fe_3O_4. The addition of magnetic powder can significantly promote the utilization of carbohydrate of the sludge alkaline fermentation liquid compared with protein during denitrification process. The present results provide some available informations to understand the effect of Fe_3O_4 on the performance of wastewater bioprocesses.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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