



Effect of flow rates on denitrifying granular sludge under different Cr(VI) concentrations

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ABSTRACT

In this study, the effects of different flow rates and different Cr(VI) concentrations on denitrifying granular sludge were investigated. Two reactors with different flow rates (1 and 2 L h⁻¹, abbreviated as R_L and R_H , respectively) were constructed and operated over four periods. From periods I to III, the influent Cr(VI) concentrations ranged from 10 to 30 mg L⁻¹, and the nitrate removal rate and Cr(VI) removal rate in R_L decreased to 97% and 85%, respectively. In addition, the suspended solids, volatile suspended solids, extracellular polymeric substances, and relative hydrophobicity in R_L were lower than those in R_H . In period IV, Cr(VI) was absent from the influent, and the denitrifying granular sludge in R_L could recover in 15 d. Inversely, the denitrification performance, Cr(VI) reduction performance and granular sludge characteristics in R_H during periods I–III were not obviously affected, which indicated that the higher flow rate helped the denitrifying granular sludge community resist the toxicity of Cr(VI) via the discharge of organo-Cr(III) complexes. These results indicated that a higher flow rate was more beneficial for the operation of upflow anaerobic sludge blanket reactors and for enabling the community to resist the toxicity of Cr(VI).

Keywords: Denitrification; Hexavalent chromium; Flow rate; Granular sludge; Upflow anaerobic sludge blanket

1. Introduction

Due to the excessive use of nitrogenous fertilizer in agriculture and inappropriate discharge of domestic and industrial wastes, nitrate has become the greatest contaminant in surface water and groundwater [1]. Nitrate can be reduced into nitrite after entering the human body, then, nitrite can produce carcinogenic nitrosamines, which are teratogenic, carcinogenic, and mutagenic toxic substances [2]. Therefore, the removal of nitrate from water is very important. Ion

exchange, electrodialysis, and reverse osmosis are conventional physical–chemical methods used to remove nitrate from water. However, the concentrated wastes generated from the above approaches require subsequent disposal, which is still a problem that needs to be solved [3]. Compared with traditional physical–chemical methods, biological methods have received increasing attention in the recent years. Due to its high efficiency and low cost, denitrification is widely applied among the different biological methods.

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He et al. [4] reported that many other contaminants could influence the removal of nitrate, such as Cr(VI), sulfate, and pesticides, which increased the difficulty of waste management. In some industries, for example, electroplating, wood preservation, and leather tanning, Cr(VI) is widely used and leads to chromium contamination in soil and groundwater. The effects of Cr(VI) on the human body mainly include teratogenicity, carcinogenesis, and mutagenicity [5,6]. Cr(VI) is highly soluble and mobile; in contrast, Cr(III) is less toxic and has a low solubility when the pH is neutral. Hence, an effective detoxification method is the reduction of Cr(VI) to Cr(III) [7]. Currently, the most commonly used chemical methods to detoxify Cr(VI) are zero-valent or ferrous iron. However, this process requires a large amount of chemicals and increases the production of sludge [8]. Therefore, biological methods could be an alternative for detoxifying Cr(VI).

Many studies have investigated the process of simultaneously removing nitrate and Cr(VI) by biological methods. Long et al. [9] developed a continuously stirred methane and oxygen-based membrane biofilm reactor (MBfR) to remove chromium from nitrate-contaminated drinking water. Zhai et al. [10] developed a spiral fiber-based biofilm reactor to investigate the simultaneous removal of nitrate and Cr(VI) under different operating parameters, including Cr(VI) concentrations, carbon, and nitrate ratios (C/Ns), hydraulic retention times (HRTs), and initial solution pH values. Li et al. [5] investigated the simultaneous removal of nitrate and chromate in an upflow packed-bed bioreactor using a biodegradable meal box as the carbon source and biofilm carriers. Miao et al. [2] used an expanded granular sludge bed (EGSB) reactor to treat high-nitrate wastewater containing different concentrations of Cr(VI) and investigated the effect of the Cr(VI) concentration on the denitrification performance and the microbial communities. However, these studies did not discuss the effect of flow rate on granular sludge under different Cr(VI) concentrations and the activity recovery of granular sludge.

Therefore, the present study aimed to investigate the effect of different flow rates on denitrifying granular sludge under different Cr(VI) concentrations in two UASB reactors. In addition, the suspended solids (SS), volatile suspended solids (VSS), extracellular polymeric substances (EPS), and relative hydrophobicity (RH) were also studied during the whole denitrification operation and activity recovery of denitrifying granular sludge.

2. Materials and methods

2.1. Sludge source and synthetic wastewater

The inoculated sludge was denitrifying granular sludge, which was acclimated with 10 mg L⁻¹ Cr(VI) in a laboratory-scale UASB reactor for 54 d. The denitrifying granular sludge was acclimated with flocculent sludge collected from the return sludge thickening tank at the Qiaoxi Municipal Wastewater Treatment Plant, Shijiazhuang, China. The SS, VSS, EPS, and RH of the denitrifying granular sludge were 51.74, 35.38 g L⁻¹, 63.38 mg g⁻¹ VSS and 48.71%, respectively.

The influent was synthetic wastewater, which contained the following compounds (g/L): NaNO₃, 0.137; KH₂PO₄, 0.01;

microelement solution (1 mg L⁻¹). The microelement solution contained the following compounds (g L⁻¹): 0.43 ZnSO₄·7H₂O, 0.014 H₃BO₄, 0.99 MnCl₂·4H₂O, 0.25 CuSO₄·5H₂O, 0.19 NiCl₂·6H₂O, and 0.24 CoCl₂·6H₂O. The Cr(VI) compound was added according to the operation of the reactors, which increased from 10 to 30 mg/L.

2.2. Reactor setup and operation

Two identical Plexiglas upflow anaerobic sludge blanket (UASB) reactors were set up to investigate the effect of different flow rates on denitrifying granular sludge under different Cr(VI) concentrations. Each reactor was 710 mm high with an inner diameter of 68 mm and a working volume of 3.5 L. A three-phase separator was equipped in the reactor. A schematic of the UASB reactor used in this study is shown in Fig. 1. The influent flow rates of the two reactors were both 1 L h⁻¹. One of them was equipped with an effluent recycling ratio of approximately 1. Thus, the flow rates of the two reactors were 1 L h⁻¹ (abbreviated as R_L) and 2 L h⁻¹ (abbreviated as R_H). The HRT of the two reactors was 3.5 h. The two reactors were operated at 35°C ± 1°C.

The reactors were operated continuously for 69 d and were divided into four periods. The effect of different Cr(VI) concentrations on the denitrifying granular sludge was investigated during periods I–III, and the activity recovery of the denitrifying granular sludge was investigated during period IV. In period I (1–18 d), the Cr(VI) influent was 10 mg L⁻¹, and then, it increased to 20 mg L⁻¹ in period II (19–36 d) and 30 mg L⁻¹ in period III (37–54 d). In period IV (55–69 d), Cr(VI) was not added to the influent of the two reactors. During the whole operation, the nitrogen loading rates (NLRs) of the two reactors were both 0.686 kg-N/(m³ d).

2.3. Methods of analysis

Cr(VI) was determined by colorimetric methods according to standard methods [11]. For total chromium analysis, the sample was first digested with a mixture of sulfuric–nitric acids and then oxidized with potassium permanganate; then, the sample was reacted with diphenyl carbazide, and the total chromium was determined spectrophotometrically. The NO₃-N, NO₂-N, SS, VSS, and RH values were measured using standard methods [11]. The EPS were extracted by the heat method according to Guo et al. [12]. The extraction procedures and measurements of extracellular polysaccharides (PS) and extracellular proteins (PN) were performed following Niu et al. [13].

3. Results and discussion

3.1. Effect of the Cr(VI) concentration on denitrification in the two reactors

The denitrification performances of the two reactors with different flow rates under different Cr(VI) concentrations are depicted in Fig. 2. As seen in Fig. 2a, in period I (1–18 d, with 10 mg L⁻¹ Cr(VI)), the effluent nitrate and nitrite concentrations of R_L were below 3 mg L⁻¹, except on day 4 and 5. This phenomenon might be due to the denitrifying granular sludge of R_L not adapting to the new

environment. During the operation of R_L , the denitrifying granular sludge of R_L was gradually adapted to the environment, and the effluent nitrate concentrations decreased. In period II (19–36 d, with $20 \text{ mg L}^{-1} \text{ Cr(VI)}$), the effluent nitrate and nitrite concentrations of R_L were below 2 mg L^{-1} .

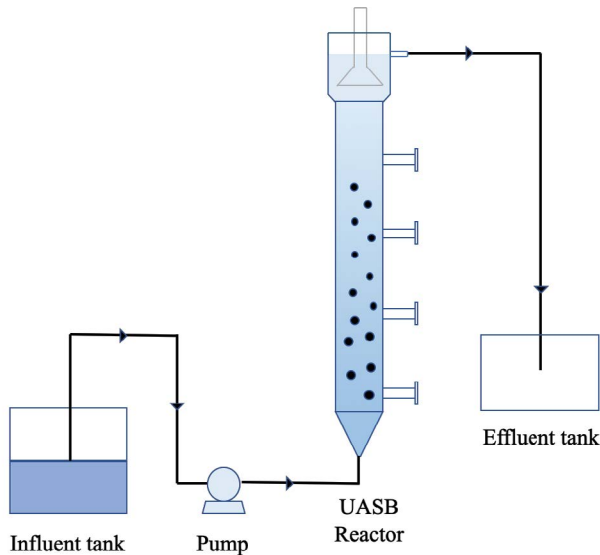


Fig. 1. Schematic of the UASB reactor.

Although the influent Cr(VI) concentration increased from 10 to 20 mg L^{-1} , the denitrification performance in R_L was not adversely affected. At day 28, due to outlet pipe plugging, the effluent nitrite concentration reached 17.63 mg L^{-1} , and it returned to normal at day 29. In period III (37–54 d, with $30 \text{ mg L}^{-1} \text{ Cr(VI)}$), the effluent nitrate and nitrite concentrations were below 1 mg L^{-1} . The denitrification performance in R_L was stable even at $30 \text{ mg L}^{-1} \text{ Cr(VI)}$. At the same time, during period I–III, the effluent nitrate and nitrite concentrations of R_H were below 0.1 mg L^{-1} (nitrate removal rate was over 99.9%), which indicated that the denitrification performance in R_H was not affected at all (Fig. 2b). These results were likely because the denitrifying granular sludge in the two reactors was acclimated to Cr(VI) and was resistant to Cr(VI) . Chang et al. [14] reported that enzyme damage from metal ions could recover in two ways: (1) replacement by new synthetic enzymes and (2) creation of new branches in cells to reduce contamination. This might be the reason that the denitrification performance in the two reactors was not adversely affected even at $30 \text{ mg L}^{-1} \text{ Cr(VI)}$.

In terms of flow rate, during the period I–III, the effluent nitrate concentrations of R_L were below 3 , 2 , and 1 mg L^{-1} , respectively. At the same time, the effluent nitrate concentrations of R_H were 0.1 , 0.1 , and 0.1 mg L^{-1} , respectively. The results of the effluent nitrate concentrations indicated that the denitrification performance of R_H was more stable than R_L , which may be due to the solubility change in Cr(III) . Cr(III) has a low solubility in neutral pH;

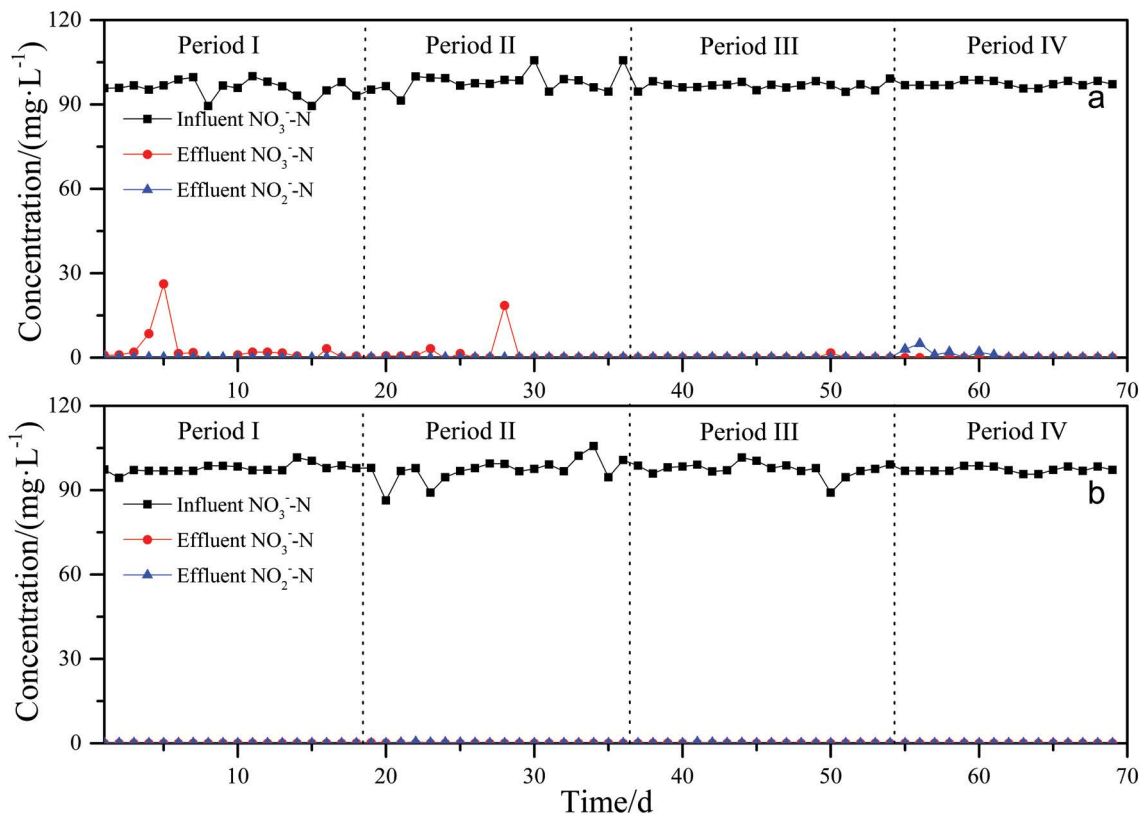


Fig. 2. Variations of the nitrate and nitrite concentrations during different periods in R_L (a) and R_H (b) (period I, with $10 \text{ mg L}^{-1} \text{ Cr(VI)}$; period II, with $20 \text{ mg L}^{-1} \text{ Cr(VI)}$; period III, with $30 \text{ mg L}^{-1} \text{ Cr(VI)}$; period IV, without Cr(VI)).

however, the solubility of Cr(III) may change because it can combine with organic substances and form organo-Cr(III) complexes [15]. Puzon et al. [16] reported that Cr(III) could react with some kinds of cellular organics to form soluble organo-Cr(III) complexes. Therefore, the unstable organo-Cr(III) complexes attached to the surface of the denitrifying granular sludge could be discharged with the flow of the effluent, leading to an enhancement of the mass transfer. The higher flow rate was more conducive to the discharge of organo-Cr(III) complexes. Another reason could be that the higher flow rate led to a larger growth in the amount of biomass [17]. Therefore, a higher flow rate is more effective for the operation of reactors.

In period IV (days 55–69, without Cr(VI)), Cr(VI) was absent in the influent to investigate the activity recovery of the two reactors. The denitrification performance of R_H was not significantly changed compared to that in period III (Fig. 2b). At the same time, the denitrification performance of R_L recovered to 100% in 15 d. The reasons for the recovery of the denitrification performance in R_L may be as follows: First, when Cr(VI) was absent from the influent, the toxicity from influent Cr(VI) to denitrifying granular sludge disappeared. Secondly, Ramirez-Diaz et al. [18] reported that nitrate and Cr(VI) may compete for electrons and have some impact on each other. When Cr(VI) was absent from the influent, electron competition also disappeared. Hence, the absence of Cr(VI) contributed to the recovery of the denitrification performance.

3.2. Effect of the Cr(VI) concentration on Cr(VI) reduction in the two reactors

The Cr(VI) removal efficiencies in the two reactors with different flow rates under different Cr(VI) concentrations are depicted in Fig. 3. As seen in Fig. 3a, in period I (1–18 d, with 10 mg L⁻¹ Cr(VI)), the effluent Cr(VI) concentration and the effluent total Cr concentration of R_L were both below 1 mg L⁻¹, and the Cr(VI) removal rate of R_L was approximately 0.34 mg Cr(VI)/(g VSS). The effluent Cr(VI) concentration of R_L was approximately equal to the effluent total Cr concentration of R_L , which indicated that Cr(III) was absorbed by the denitrifying granular sludge. In period II (19–36 d, with 20 mg L⁻¹ Cr(VI)), when the influent Cr(VI) concentration increased from 10 to 20 mg L⁻¹, the effluent Cr(VI) concentration and the effluent total Cr concentration of R_L increased to approximately 3 mg L⁻¹ (day 19), and then they returned to 1 mg L⁻¹ at day 20. This phenomenon indicated that the denitrifying granular sludge of R_L was gradually adapted to 20 mg L⁻¹ Cr(VI). As seen in Fig. 2a, the effluent nitrate concentration of R_L fluctuated on day 23, which was later than the fluctuation of the effluent Cr(VI) concentration. He et al. [4] reported that the lag in inhibition of the denitrification process was ascribed to the electron competition between Cr(VI) and nitrate, which was also found in another study [10]. From day 20 to 36, the effluent Cr(VI) concentration and the effluent total Cr concentration were below 1 mg L⁻¹, and the effluent Cr(VI) concentration of R_L was still approximately equal to the effluent total Cr concentration. The Cr(VI) removal rate of R_L in period II was approximately 0.35 mg Cr(VI)/(g VSS). Although the influent Cr(VI) concentration increased from 10 to 20 mg L⁻¹,

the Cr(VI) reduction in R_L was not adversely affected. In period III (37–54 d, with 30 mg L⁻¹ Cr(VI)), when the influent Cr(VI) concentration increased from 20 to 30 mg L⁻¹, the effluent Cr(VI) concentration and the effluent total Cr concentration of R_L increased to approximately 2 mg L⁻¹, and the Cr(VI) removal rate of R_L was approximately 0.33 mg Cr(VI)/(g VSS). Similarly, at the beginning of period III (day 38), the effluent Cr(VI) and total Cr concentrations were approximately 7.5 mg L⁻¹, which may be because the denitrifying granular sludge of R_L was not adapted to the increased Cr(VI) concentration. At day 39, the effluent Cr(VI) concentration and the effluent total Cr concentration recovered to 2 mg L⁻¹. The effluent Cr(VI) concentration and the effluent total Cr concentration of R_L increased from 1 mg L⁻¹ (period I) to 2 mg L⁻¹ (period II). Thus, the further increase in Cr(VI) concentration slightly affected the activity of the denitrifying granular sludge. During period I–III, the Cr(VI) reduction in R_L was maintained over 85%. At the same time, as seen in Fig. 3b, from period I to III, the effluent Cr(VI) concentration of R_H was below 0.1 mg L⁻¹, the Cr(VI) reduction in R_H was maintained over 99%, and the effluent total Cr concentrations of period I–III were 5, 17.5, and 25 mg L⁻¹, respectively. The Cr(VI) removal rates of R_H in the three periods (i.e., I–III) were approximately 0.26 mg Cr(VI)/(g VSS), 0.34 mg Cr(VI)/(g VSS), and 0.38 mg Cr(VI)/(g VSS), respectively. The effluent Cr(III) concentration of R_H could be obtained by subtracting the effluent total Cr concentration and the effluent Cr(VI) concentration, and during the period I–III, the effluent Cr(III) concentrations were 4.9, 17.4, and 24.9 mg L⁻¹, respectively. The effluent Cr(III) concentrations of R_H were higher than those of R_L . At the same time, the removal rate of nitrate of R_H was maintained over 99%. These phenomena indicated that the activity of denitrifying granular sludge in R_H was not influenced even if the Cr(VI) concentration was 30 mg L⁻¹. In period IV, due to the absence of Cr(VI), the effluent Cr(VI) concentrations of the two reactors were not detected, and the effluent total Cr concentrations of R_L and R_H were approximately 2.5 and 6.5 mg L⁻¹, respectively. Thus, the effluent Cr(III) concentrations of R_L and R_H were approximately 2.5 and 6.5 mg L⁻¹, respectively. This phenomenon indicated that Cr(III) could flow out of the reactors. When Cr(III) flowed out of the reactors, the mass transfer between the nutrients and denitrifying granular sludge was improved, which contributed to the recovery of denitrifying granular sludge.

In terms of flow rate, during the whole operation, the reduction in Cr(VI) was observed, and a large amount of the generated Cr(III) was removed with the effluent. The effluent Cr(III) concentrations of R_H were 5, 17.5, and 27.5 mg L⁻¹ in periods I–III, respectively. The effluent Cr(III) concentration of R_H in period IV decreased gradually from 8 mg L⁻¹ to a concentration too low to be detected. In contrast, the effluent Cr(III) concentrations of R_L were not detected in periods I and II. In the periods III and IV, the effluent Cr(III) concentrations of R_L were 0.5 and 1 mg L⁻¹, respectively. The effluent Cr(III) concentrations of R_H were higher than those of R_L . This phenomenon showed that the higher flow rate led to the shedding of soluble organo-Cr(III) complexes on denitrifying granular sludge. Moreover, the surface of R_L 's denitrifying granular sludge turned virescent, which also indicated that a part of the reduced Cr(III) was adsorbed

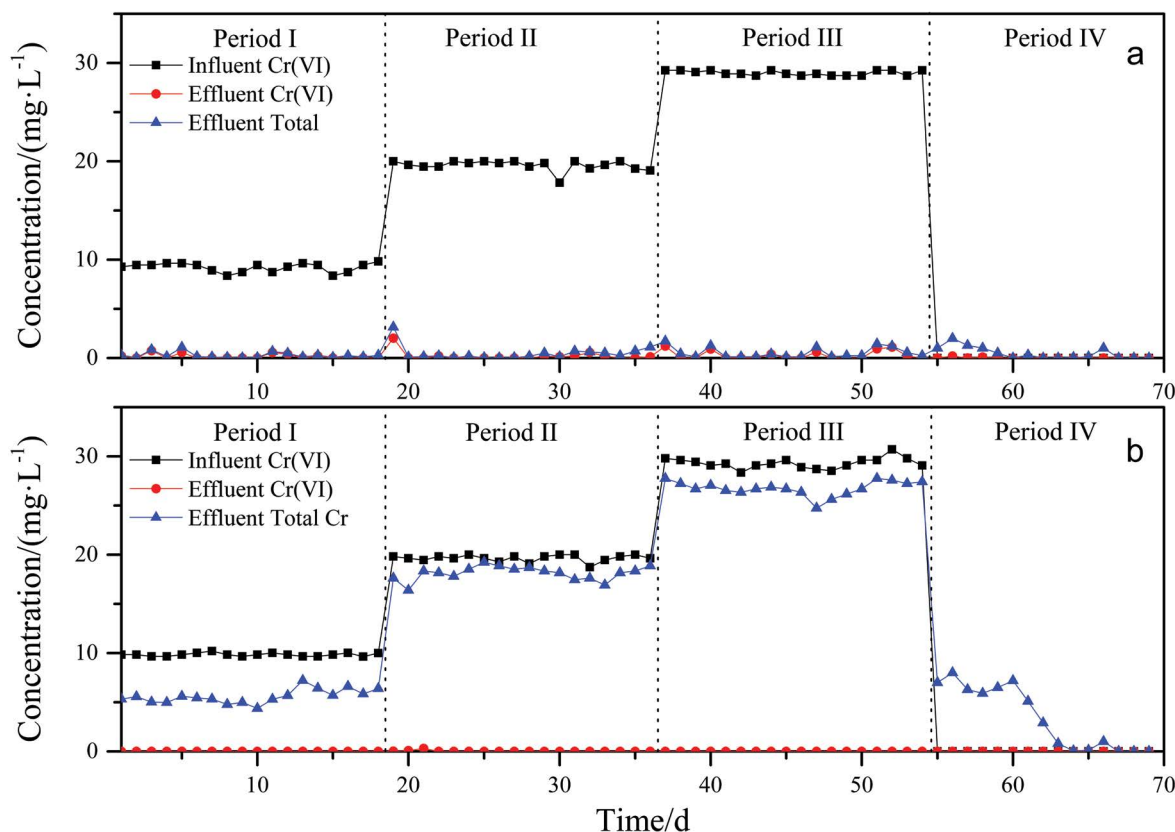


Fig. 3. Variations of influent Cr(VI), effluent Cr(VI), and effluent total Cr concentrations during different periods in R_L (a) and R_H (b).

on the surface of the denitrifying granular sludge. On the basis of the above results, in practical operation, the flow rate should be properly increased according to the influent Cr(VI) concentration in wastewater, which would not only improve the denitrification performance but also reduce the toxicity of the toxic substances to the sludge.

3.3. Effect of the Cr(VI) concentration on characteristics of the granular sludge in the two reactors

To investigate the effect of the Cr(VI) concentration on the denitrifying granular sludge under the different flow rates, the granular sludge characteristics (SS, VSS, EPS, and RH) were evaluated. The granular sludge characteristics of the two reactors under varying Cr(VI) concentrations are depicted in Table 1.

3.3.1. SS and VSS characteristics

The initial SS of R_L and R_H were both 51.74 g L⁻¹, and the initial VSS of R_L and R_H were both 35.38 g L⁻¹. In period I (1–18 d, with 10 mg L⁻¹ Cr(VI)), the SS and VSS of R_L slightly declined. Because the denitrifying granular sludge of R_L was not adapted to the new environment, the denitrifying granular sludge in R_L was gradually disintegrated and flowed out with the effluent. This phenomenon was consistent with the denitrification performance and Cr(VI) reduction of R_L in period I. In period II (19–36 d, with 20 mg L⁻¹ Cr(VI)) and period III (37–54 d, with 30 mg L⁻¹

Cr(VI)), although the Cr(VI) increased from 10 to 30 mg L⁻¹, the SS and VSS of R_L increased to 119.58 and 108.73 g L⁻¹, respectively. This phenomenon indicated that the denitrifying granular sludge in R_L was gradually adapted to Cr(VI), which was also consistent with the denitrification performance and Cr(VI) reduction of R_L in period II and period III. In contrast, from period I to III, the SS and VSS of R_H increased. The SS of R_H increased from 51.74 to 143.66 g L⁻¹, and the VSS of R_H increased from 35.38 to 131.45 g L⁻¹. This phenomenon was consistent with the denitrification performance and Cr(VI) reduction in R_H . Although the influent Cr(VI) concentration increased from 10 to 30 mg L⁻¹, the SS of the two reactors increased. In period IV, the SS of R_L increased from 119.58 to 131.92 g L⁻¹, and the VSS of R_L increased from 108.73 to 130.77 g L⁻¹. The SS of R_H increased from 143.66 to 161.43 g L⁻¹, and the VSS of R_H increased from 131.45 to 153.61 g L⁻¹.

In terms of flow rate, during the whole operation, the SS and VSS of R_L increased from 51.74 and 35.38 g L⁻¹ to 131.92 and 130.77 g L⁻¹, respectively; the SS and VSS of R_H increased from 51.74 and 35.38 g L⁻¹ to 161.43 and 153.61 g L⁻¹, respectively. The increases in SS of R_L and R_H were 12.34 and 17.77 g L⁻¹, respectively, and the increases in VSS of R_L and R_H were 22.04 and 22.16 g L⁻¹, respectively. The increases in SS and VSS in R_H were larger than those in R_L , which indicated that a higher flow rate is beneficial for the growth of the denitrifying granular sludge. It is possible that the unstable organo-Cr(III) complexes attached to the surface of the denitrifying granular sludge were discharged with the

Table 1
Characteristics of denitrifying granular sludge in R_L (a) and R_H during the whole operation

Sludge characteristics	Reactor	Time (d)						
		0 [*]	13 ^a	27 ^b	40 ^c	54 ^c	61 ^d	69 ^d
SS (g L ⁻¹)	R_L	51.74	45.67	63.19	81.60	119.58	125.67	131.92
	R_H	51.74	55.67	72.15	91.6	143.66	154.33	161.43
VSS (g L ⁻¹)	R_L	35.38	29.00	39.67	69.00	108.73	112.46	130.77
	R_H	35.38	39.11	58.67	79.05	131.45	132.67	153.61
EPS (mg g ⁻¹ VSS)	R_L	63.38	68.64	85.43	84.63	92.55	89.05	89.61
	R_H	63.38	69.63	81.34	75.43	90.49	91.79	93.14
Relative hydrophobicity (%)	R_L	48.71	52.69	63.92	65.07	67.37	68.20	66.11
	R_H	48.71	55.38	67.44	78.18	85.64	86.30	83.19

*inoculated sludge.

^aperiod I (day 1–18, with 100 mg L⁻¹ nitrite and 10 mg L⁻¹ Cr(VI))

^bperiod II (day 19–36, with 100 mg L⁻¹ nitrite and 20 mg L⁻¹ Cr(VI))

^cperiod III (day 37–54, with 100 mg L⁻¹ nitrite and 30 mg L⁻¹ Cr(VI))

^dperiod IV (day 55–69, with 100 mg L⁻¹ nitrite)

higher flow of water, which led to the downward trend of the inorganic degree of denitrifying granular sludge. In addition, the denitrification and Cr(VI) reduction performance of R_H was steadier than that of R_L , which was consistent with the SS and VSS characteristics of R_L and R_H .

3.3.2. EPS characteristics

The initial EPS of R_L and R_H were both 63.38 mg g⁻¹ VSS. From period I to III, the EPS of the R_L increased from 63.38 to 92.55 mg g⁻¹ VSS, and the EPS of the R_H increased from 63.38 to 90.49 mg g⁻¹ VSS. Although the Cr(VI) influence increased from 10 to 30 mg L⁻¹, the EPS of the two reactors both increased. This phenomenon indicated that the denitrifying granular sludge of the two reactors was adapted to Cr(VI), which could stimulate the secretion of EPS. In addition, the EPS of R_H was lower than that of R_L . This phenomenon may be due to the higher flow rate leading to the outflow of EPS of denitrifying granular sludge in R_H . In period IV, the EPS of the R_L decreased from 92.55 to 89.61 mg g⁻¹ VSS; in contrast, the EPS of the R_H increased from 90.49 to 93.14 mg g⁻¹ VSS.

In terms of flow rate, during the whole operation, the EPS of R_L increased from 63.38 to 89.61 mg g⁻¹ VSS, and the EPS of R_H increased from 63.38 to 93.14 mg g⁻¹ VSS. The increases in EPS of R_H were larger than those in R_L , and combined with the trends of SS and VSS, the higher flow rate is beneficial for the growth of the denitrifying granular sludge.

3.3.3. Relative hydrophobicity characteristics

The initial RH of R_L and R_H were both 46.86%. During period I–III, the RH of the R_L increased from 48.17% to 67.37%, and the RH of R_H increased from 48.17% to 85.64%, respectively. Although the influent Cr(VI) concentration increased from 10 to 30 mg L⁻¹, the RH of the two reactors both increased. This phenomenon indicated that the denitrifying granular sludge of the two reactors was adapted to Cr(VI), which demonstrated that the existence of Cr(VI) could lead to the increased hydrophobicity of denitrifying granular sludge. It has been reported that PN

and PS in EPS are hydrophobic and hydrophilic components, respectively; microorganisms in denitrifying granular sludge could secrete more PN to protect themselves from the toxicity of Cr(VI), which leads to an increase in the RH of granular sludge [19,20]. In period IV, the RH of the R_L decreased from 67.37% to 66.11%, and the RH of the R_H decreased from 85.64% to 83.19%. This may be because the disappearance of Cr(VI) led to the decreased secretion of PN in microorganisms; therefore, the relative hydrophobicity of the two reactors declined.

In terms of flow rate, during the whole operation, the RH of R_L increased from 48.17% to 66.11%, and the RH of R_H increased from 48.17% to 83.19%. The increases in RH in R_H were larger than those in R_L , and combined with the trends of SS, VSS, and EPS, a higher flow rate is beneficial for the growth of denitrifying granular sludge.

4. Conclusions

This study investigated the effects of different flow rates on denitrification performances under different concentrations of Cr(VI). The results of the denitrification performance, Cr(VI) reduction performance and granular sludge characteristics in this study indicated that the denitrifying granular sludge was not obviously influenced by 10–30 mg L⁻¹ Cr(VI). Furthermore, the effect of Cr(VI) on denitrifying granular sludge was reversible. In addition, the higher flow rate was beneficial to discharge organo-Cr(III) complexes from the reactor, which ensured that the UASB reactors could maintain the denitrification performances. Therefore, increasing the flow rate of the reactor was a more effective method for enabling the sludge community to resist the Cr(VI) toxicity. These findings may provide a promising strategy for the treatment of nitrogen wastewater containing toxic pollutants.

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