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Original Research

Application of Primary Sludge Fermentation for the Production of Carbon Source for Full-Scale Biological Nutrients Removal

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Abstract

The wastewater effluent quality in BNR systems critically depends on the availability of readily biodegradable carbon source in the influent. Primary sludge in WWTPs is identified as a renewable resource for internal carbon source production. The effects of SRT, temperature and RR on the anaerobic fermentation process performance were assessed and the biological nutrient removal performance was evaluated in this study. The results showed SRT of 5d, temperature of 30ºC and RR of 20 is the optimal operating condition for primary sludge anaerobic fermentation. Under the optimal operating condition, the SCOD and VFA production rate of the fermentation product is in the range of 0.39~0.48 mg SCOD/mg VSS and 0.25~0.31 mgVFA/mg VSS. The full-scale application of internal carbon source production has achieved better effluent quality (TN 7.1 mg/L and TP 0.3 mg/L) compared to the effluent (TN 18.4 mg/L and TP 1.3 mg/L) without adding carbon source. Primary sludge fermentation can be considered as an appropriate solution for carbon source production and contribute to the goal of meeting stringent wastewater discharge standard.

Keywords: wastewater treatment, primary sludge, anaerobic fermentation, carbon source, biological nutrient removal

Introduction

The activated sludge process is widely used in biological treatment of municipal and industrial wastewater for its cost-effective removal of organic matter, nitrogen, and phosphorus. The most common biological nutrient removal (BNR) processes applied in wastewater treatment plants (WWTPs) are anaerobic/anoxic/oxic (A/A/O), Bardenpho and sequencing batch reactor (SBR) and so on [1-3]. From the point of nationwide, the number of WWTPs equipped with BNR is increasing in China. Many studies and practical experience have evidenced that the biodegradable soluble chemical oxygen demand (SCOD) and volatile fatty acids (VFA) in the influent is one of the principal factors affecting the magnitude of the nutrient removal [4, 5]. Sewer leakage is the main determining factor conducting to China's low C/N ratio of wastewater [2]. Due to the low C/N ratio of wastewater influent,

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the BNR performance is limited for insufficient carbon source that can be directly used by denitrifying bacteria and phosphorus accumulating bacteria. Therefore it is hard for the WWTPs to meet more stringent nitrogen and phosphorus discharge standard without supplying carbon source [6]. Recently, many WWTPs are extensively using external carbon sources such as methanol, ethanol and sodium acetate in the anoxic tank to promote the denitrification process [7, 8]. However, adding eternal carbon source is not considered a sustainable way because of the high capital cost and the inconvenient transportation. For the conventional activated sludge wastewater treatment process, large amounts of sludge, as by-products, are generated and generally not being properly recycled in many occasions [9, 10]. As the wastewater-sourced sludge is mainly composed of organic matter, the valorization of sludge is attracting more and more attention, in particular to producing carbon source on-site [11-13]. The dose of produced internal carbon source rather than commercial organic carbon source would not only reduce the cost but also decrease the sludge production in WWTP. It was reported that the total short chain fatty acids (SCFAs) production from wasted activated sludge (WAS) could shrink about 60% of carbon gap of the current WWTPs in China and considerable costs could be reduced [14]. The hydrolysis and acidification of primary sludge (PS) as well as the WAS in the WWTPs is identified as an important route to produce internal carbon. It is believed that hydrolysis is the rate-limiting step for SCFAs production by sludge fermentation [15]. Thus, many researchers have investigated acid or alkaline fermentation of PS and WAS as a VFA source to improve BNR performance [16-18]. In order to enhance and optimize the VFA production, the effects of anaerobic fermentation conditions such as temperature, pH [17,19], mixing [18], sludge retention time (SRT) [20] were studied. In particular, high VFA production and solubilization of PS was obtained under thermophilic conditions with pH in the range of 7 to 11 [21]. The maximum SCOD and VFA production was achieved at the optimal conditions of SRT of 6 days and 20ºC [22]. However, those studies solely focused on the full-scale application of produced carbon source to BNR process in WWTP.

Usually, PS that has higher organic content than the WAS is preferred in terms of producing carbon source. In this study, the PS anaerobic fermenter was installed and the produced carbon source was applied to full-scale NRR process in anoxic tank. The effects of SRT, fermentation temperature and recirculation ratio (RR) on the SCOD and VFA production were studied. Meanwhile, the performance of nitrogen and phosphorus removal efficiency was compared with adding carbon source and without adding carbon source. The objective of this study was to provide an optimal operating condition for primary sludge anaerobic fermentation at the WWTP and ensure the effluent quality meets stringent nitrogen and phosphorus discharge standard limit.

Materials and Methods

Description of Changqiao WWTP

Changqiao WWTP, initially built in 1989, is located in Xuhui district of Shanghai with wastewater treatment scale of 4.0×10^4 m^3/d. An A^2/O (anaerobic/anoxic/oxic) process was adopted for wastewater secondary biological treatment for nutrients removal. The first Class B discharge standard was adopted during the period of this study. The ratio BOD_5/TN for the influent wastewater ranges from 2.5 to 2.8 which indicated that the carbon source is insufficient for the denitrification. The average value of BOD_5, SS, COD, ammonium, TN and TP for the effluent currently is 10.3, 11.9, 38.2, 4.57, 14.61, 0.95 mg/L respectively. As more stringent effluent discharge regulations were implemented, the WWTP in this study has been striving to improve the effluent quality in order to meet the first Class A discharge standard for WWTPs in China. The key to achieving this goal is to further reduce the nitrogen and

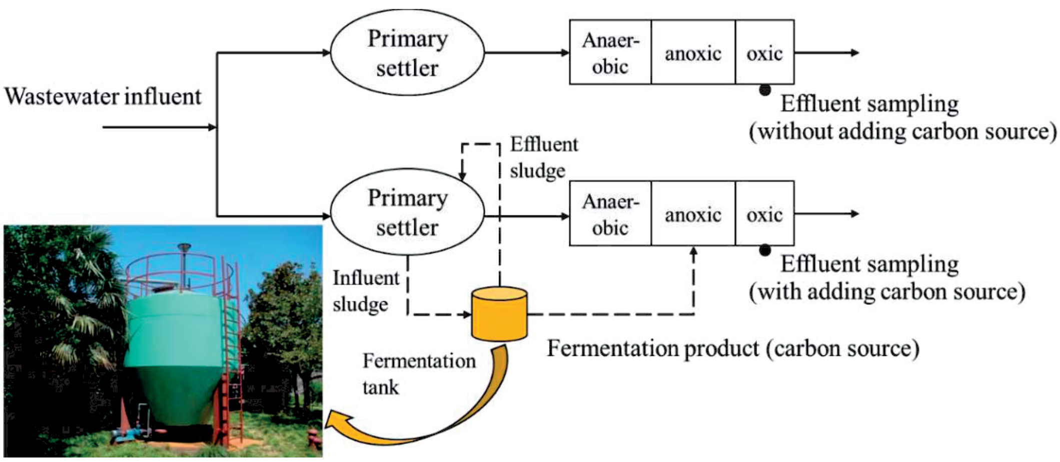

Fig. 1. Primary sludge fermentation for producing carbon source at Changqiao WWTP.

phosphorus content of the effluent. Thus a full-scale carbon source preparation by means of PS anaerobic fermentation was installed onsite to enhance the nutrients removal (Fig. 1).

Description of Carbon Source Production

The fermentation tank for carbon source production at Changqiao WWTP has a diameter of 3 m, a height of 4 m, and an effective volume of 16 m^3. The PS from one group of the primary settlers was pumped into the fermentation tank and the flowrate, pH and temperature were monitored real-time. The sludge was stirred by hydraulic circulating at a certain RR which is expressed as sludge recirculation flowrate/sludge inflow rate. The HRT almost equals SRT as it is a completely mixed fermenter. The temperature of the fermentation tank was controlled by electrothermal heat pump. The carbon source (fermentation product) obtained through the anaerobic acid production reaction was added into the anoxic zone of the reaction tank through a dosing pump to facilitate biological nitrogen and phosphorus removal. The parameters of raw PS for carbon source production is presented in Table 1.

Operation Conditions

The Changqiao plant has two groups of biological nutrients removal tanks, one for adding carbon source, and the other for maintaining the original operating conditions for comparison. In order to achieve an optimal operational condition, the influence of temperature, SRT as well as RR on the microbial activity and VFA production was investigated. First, different SRT of 3, 5 and 8 days were chosen to assess the anaerobic fermentation performance. Then, different temperature of 20, 30 and 40ºC at SRT = 5 days were investigated for the anaerobic fermentation evaluation. Furthermore, different RR of 10, 20 and 30 were investigated for the anaerobic fermentation evaluation.

Sampling

The sampling campaign was conducted to assess the performances of PS fermentation and biological nutrients removal process. The fermentation effluent samples were taken from the PS fermentation tank and the wastewater samples from the oxic tank with and without adding carbon source. The samples were first centrifuged at 10,000 rpm for 10 min, and then were filtered with 0.45 µm syringe filters. The samples were analyzed for the main parameters twice a day.

Table 1. The average value and standard deviation of raw primary sludge.

Parameter	Value	Unit
pH	7.05±0.38	-
SCOD	1012±98	mg/L
VFA	698±132	mg/L
Moisture content	97.3±1.2	%
MLSS	25.4±3.1	g/L
MLVSS	13.5±2.3	g/L

Analytical Methods

The concentration of total suspended solid (TSS), volatile suspended solid (VSS), SCOD and pH measurements were performed according to Standard Methods [23]. The VFA concentration was determined by titration according to the method proposed by [24]. The VFA composition was determined by a gas chromatography (GC-2010, Japan), equipped with a flame ionization detector (FID) and a fused-silica capillary column (PEG-20 M, 30 m×0.32 mm×0.5 l m, China). Nitrogen gas flow rate was 50 mL/min. The column temperature was maintained at 110ºC initially. While, the highest temperature was 220ºC, and then was held for 2 min. Both the injection port and detector temperatures were 220ºC.

Results and Discussion

Influence of SRT, Temperature and SRR on Fermentation Performance

Fig. 2a) shows the pH, SCOD and VFA concentration in the fermented sludge at different SRT. The SCOD and VFA concentration of the fermentation product slightly fluctuated at SRT of 3d, then rapidly increased when the SRT was 5 days. The pH value decreased from 6.8 during SRT of 3d to 6.2 during SRT of 5d. It is observed that SRT of 3d was not long enough for VFA production. The reason is that the acid-producing bacteria that had not grown sufficiently was discharged from the fermenter. By contrast, anaerobic hydrolysis was sufficient to produce acid and it greatly exerted anaerobic acid-producing ability at the SRT of 5d. Compared with the raw PS, the SCOD at the SRT of 5d concentration was improved by 527.2% and the VFA by 378.7%.

From SRT of 5d to 8d, the SCOD and VFA concentration of the fermentation product decreased because the organic loading environment corresponding to SRT of 8 days beneficial to the growth of acetic acid methanogens. In this case, the VFAs produced by acid producing bacteria were easily consumed by the acetic acid methanogens in the system [25], which is manifested as a decrease in the SCOD level of the effluent of the system. As a consequence, the SRT of 5d showed higher SCOD and VFA production rate, 0.5 to 2.0 times, than that of SRT of 3d and 8d (see Fig. 3). Thus, the SRT must be kept low to avoid (at least minimize) the methanogenesis.

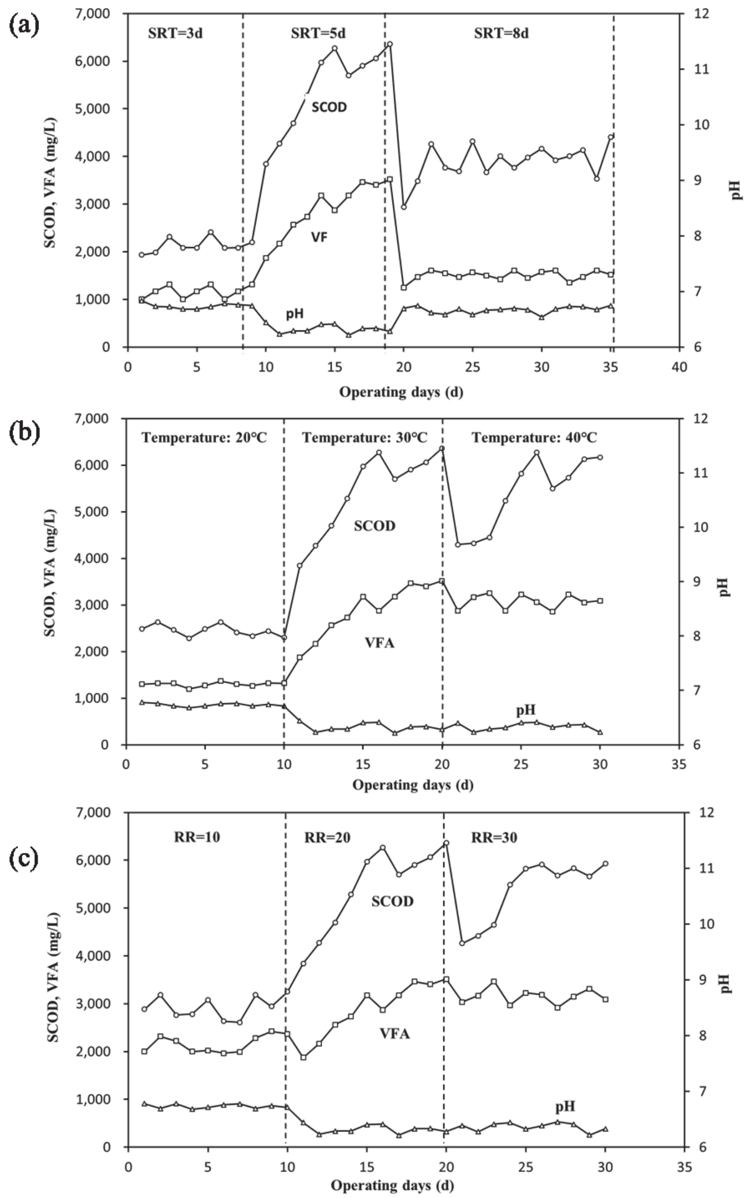

Fig. 2. pH, SCOD and VFA variation at different SRT a), temperature b) and RR c).

Under the condition of SRT = 5 days, the effects of different temperature on the fermentation performance were assessed. Temperature affects the reaction rate of microorganisms, thereby affecting the efficiency of the system to produce carbon sources. It can be seen from Fig. 2b) that when the fermentation temperature is 20°C, the SCOD and VFA in the fermentation product fluctuate within a certain range, ranging from 2010 to 2710 mg/L and 1001 to 1465 mg/L, respectively. When the fermentation temperature rose to 30ºC, the SCOD and VFA in the fermentation product gradually increased, and the ranges are 3915~6255mg/L and 1921~3641mg/L, respectively. Compared with the raw PS, the production of SCOD and VFA was increased by 3~4 times. Meanwhile, the pH value around 6.2 indicated that the acid production was relatively sufficient. It is inferred that the activity of anaerobic acid producing bacteria in the whole system was greatly improved. When the fermentation temperature is 40°C, it showed the similar performance to the temperature of 30ºC in terms of the SCOD and VFA concentration as well as the production rate (see Fig.3). Although it was pointed out increasing the temperature will generally increase the production of VFA yield [26,27], the result in this study showed the temperature of 30℃ is the most efficient and economically favorable temperature. Some studies have reported that mesophilic temperature (35ºC) is the optimal parameter as the VFA production was the highest or similar to that under higher temperatures [28-30].

As shown in Fig. 2c), when the RR was 20, the dissolution of SCOD (3915~6255 mg/L) and VFA (1921~3641 mg/L) in the fermentation product was much better than the RR of 10. The pH range was 6.2 to

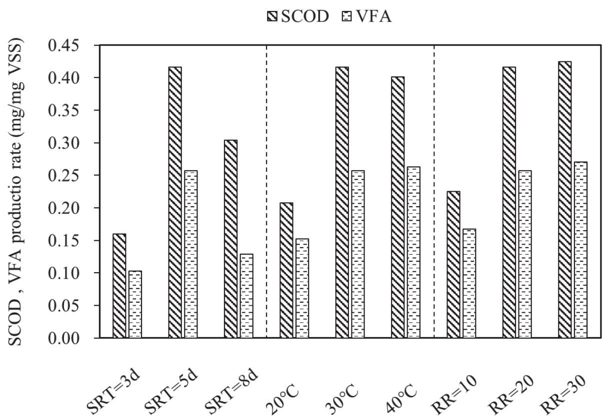

Fig. 3. SCOD and VFA production rate at different SRT, temperature and RR.

6.3 indicating that the anaerobic hydrolysis was sufficient for acid production, and the entire system was in a good anaerobic fermentation acid production environment. Therefore, the anaerobic acid producing bacteria could produce more acid at this stirring intensity. It is obvious that the fermentation performance as good as RR of 20 was achieved when RR was 30 in terms of SCOD and VFA production rate. However, the energy consumption and the operating cost would be rising as the stirring intensity continued to increase.

It was obviously found that the VFA production rate increased by anaerobic fermentation compared to the raw PS. The short chain fatty acids such as acetic acid, propionic acid and butyric acid are most easily utilized by the denitrifying bacterial. As presented in Table 2, the percentage of the acetic acid was the highest among the VFA compositions. Over 40% of VFA was detected as acetic acid when the PS fermented at SRT of 5d, temperature of 30ºC and RR of 20. The acetic acid fraction in this study is significantly lower than the reported results that acetic acid was the overwhelming acid (over 80%) in total VFAs [31].

Influence of SRT, Temperature and SRR on Biological Nutrients Removal

The carbon source prepared by the sludge anaerobic fermentation was added to one anoxic tank and the other one was set as control. The effluent TN and TP concentration were monitored and the removal efficiencies were calculated correspondingly. As the PS used in for carbon source preparation was also the nitrogen and phosphorus source, the TN and TP concentration in the fermentation product was analyzed to investigate the impact on the TN and TP removal efficiencies in the WWTP. Fig. 4 shows the TN and TP concentration of the fermentation product under different operating conditions. As far as the SRT was concerned, SRT of 8d led to a large increase of TN and TP concentration compared to SRT of 3d and 5d. Similarly, high RR and temperature resulted in higher concentration of TN than low RR and temperature, however no obvious change was observed for TP concentration. The highest TN concentration values of 162.5 mg/L, 118.8 mg/L and 210.0 mg/L were observed at SRT of 8d, RR of 30 and 40ºC respectively, more than two times of the influent TN concentration (53 mg/L). Considering the diversion of nitrogen and phosphorus load to anoxic tank, SRT of 8d, RR of 30 and fermentation temperature of 40ºC were not suitable operating conditions for carbon source preparation.

The influence of carbon source on the removal of nutrients was depicted on Fig. 5 and Fig. 6. The effluent TN and TP content with adding carbon source prepared under different SRT conditions were all lower than that without adding carbon source as expected. The TN content 7.9 mg/L and TP content 0.4 mg/L of the effluent were observed under SRT of 5d (see Fig. 5) and the corresponding TN and TP removal efficiencies were 86.8% and 93.5% (see Fig. 6). The TN and TP removal efficiencies were improved more at SRT of 5d than they were at SRT of 3d and 8d. This was mainly because higher VFA production rate that is beneficial

Table 2. The VFA composition content under different operation conditions.

Parameters		Acetic acid (%)	Propionic acid (%)	Butyric acid (%)
SRT (d)	3	18.3	10.3	5.2
	5	40.2	18.9	10.3
	8	20.1	15.2	8.2
Temperature (ºC)	20	21.3	13.3	8.2
	30	40.2	19.3	10.0
	40	34.2	18.2	11.2
RR	10	29.3	15.3	7.8
	20	41.2	19.2	10.1
	30	38.6	19.5	11.2
Raw primary sludge		1.11~2.23	0.05~1.84	1.23~3.01

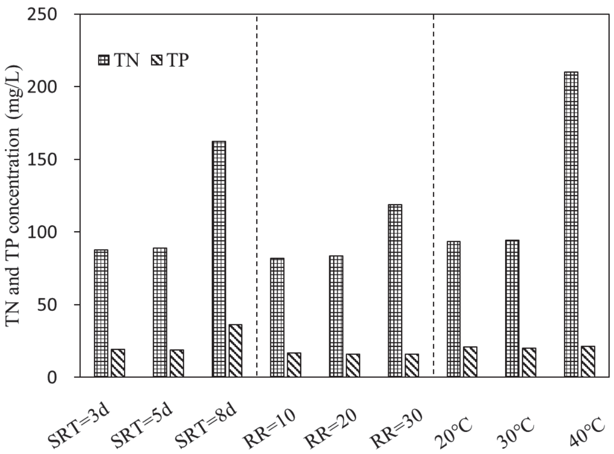

Fig. 4. The TN and TP concentration of the sludge anaerobic fermentation product.

for denitrifying was obtained at SRT of 5d than SRT of 3d and 8d. Other than that, high TN and TP content of sludge fermentation product at SRT of 8d would adversely affect the removal efficiency.

As for the fermentation temperature, the effluent TN and TP concentration was decreased by adding carbon source prepared at 20ºC, 30ºC and 40ºC. Due to the higher VFA production, adding carbon source at 30ºC led to lower effluent TN and TP concentration than 20ºC and 40ºC, ensuring the effluent quality meet the Class1A of Chinese wastewater discharge standard. The TN and TP removal efficiency was improved to 87.1% and 93.1% compared to that without adding carbon source.

With respect to the sludge RR, better effluent quality and higher TN and TP removal efficiencies was obtained at RR of 20 compared to that at RR of 10 and 30. This outcome could be explained by more VFA production at RR of 20.

Based on the above results and analysis, it could be found the carbon source produced in PS anaerobic fermentation under the set experimental conditions was helpful to improve TN and TP removal efficiency. The optimal operating condition for PS anaerobic fermentation should be SRT of 5d and temperature of 30°C and sludge RR of 20 in terms of effluent quality and nutrients removal efficiency.

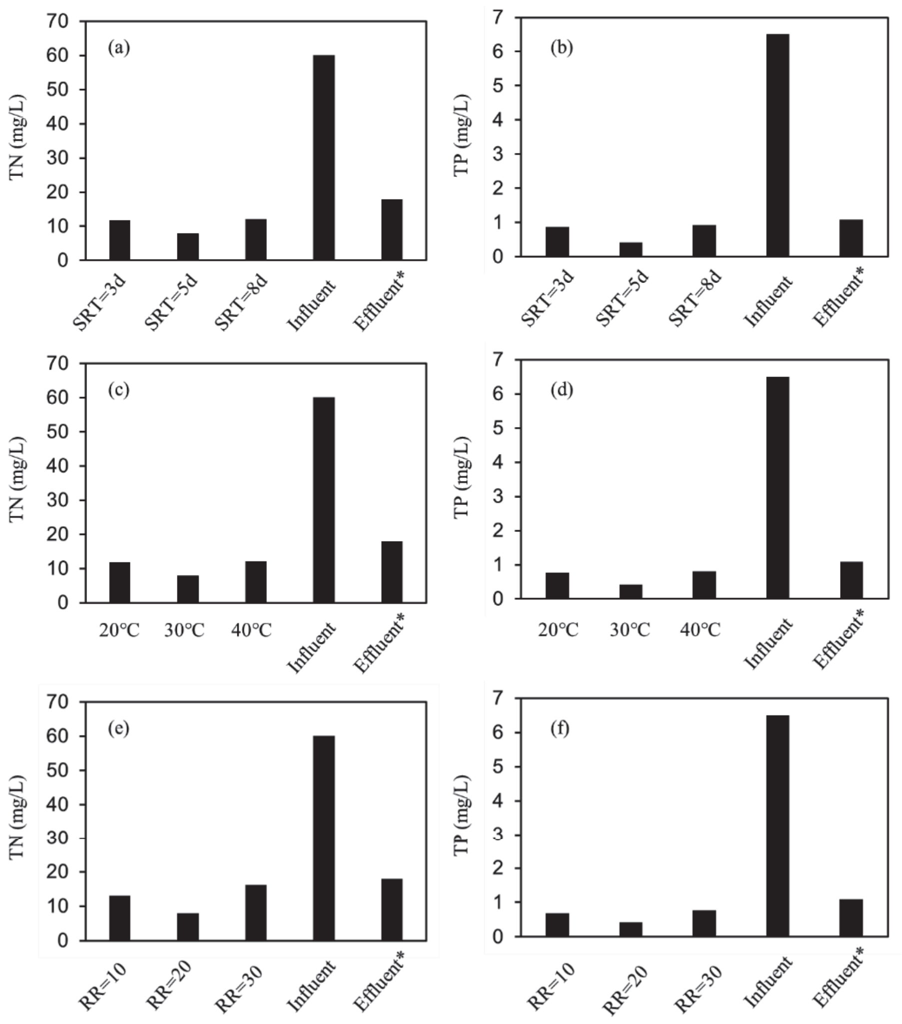

Fig. 5. The TN a), c), e) and TP b), d), f) content of the effluent. Effluent* means the effluent without adding carbon source.

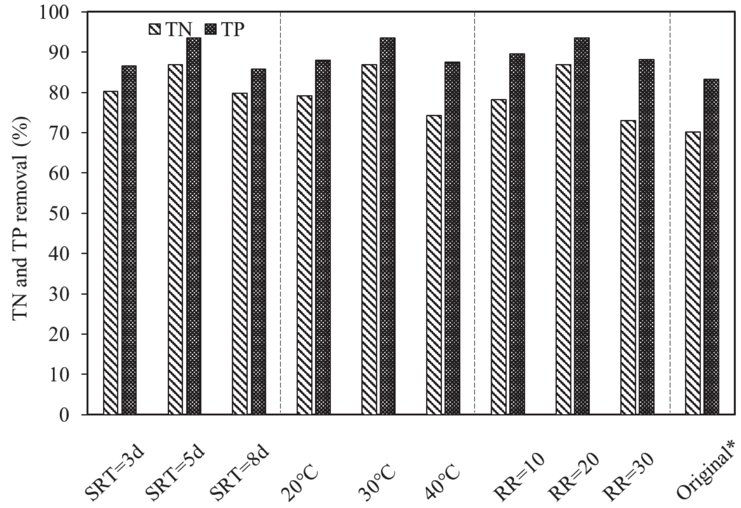

Fig. 6. The TN and TP removal efficiency of biological treatment process. Original* means the removal efficiency without adding carbon source.

Optimal Operation Performance

The PS anaerobic fermentation configuration was operated under optimal conditions (i.e. SRT of 5d, temperature of 30ºC, and RR of 20) for 15 days. The SCOD and VFA concentration of the fermentation product was in the range of 5812~6389 mg/L and 2312~3810 mg/L respectively. The SCOD and VFA production rate of the fermentation product was in the range of 0.39~0.48 mg SCOD/mg VSS and 0.25~0.31 mgVFA/mg VSS. Meanwhile, the VFA in the fermentation product accounts for 61.1%~67.5% of SCOD production. It has been reported that the content and composition of VFAs in wastewater affects the biological nutrients removal [32]. It is agreed that acetic acid is the best carbon source for the biological removal of phosphorus, followed by propionic acid [33].

Among the VFA compositions, the observed acetic acid, propionic acid and butyric acid ratio were in the range of 38.7~42.5%，18.5~22.4%，8.9%~12.5%, and the sum of three acid components accounted for over 70% of the VFA production. During the optimal operation period, the effluent TN and TP were in the range of 15.5~21.2 mg/L and 1.04~1.68 mg/L respectively without carbon source addition, whereas, the effluent TN and TP were in the range of 6.0~8.9 mg/L and 0.19~0.66 mg/L respectively with carbon source addition. The average TN and TP removal efficiency were 88.2% and 92.8%. The effluent could meet first Class A discharge standard.

Conclusions

This study operated a PS anaerobic fermentation configuration at a WWTP for carbon source production, and the carbon source was added to a full-scale anoxic tank to observe the nutrients removal. The full-scale experiments revealed that SRT of 5d, temperature of 30ºC and RR of 20 was the optimal operating condition for PS anaerobic fermentation in terms of SCOD and VFA production. The principal components of the VFA are acetic acid, propionic acid and butyric acid. The addition of the prepared carbon source could improved the effluent quality and enhanced the nutrients removal efficiency.

Acknowledgments

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Conflict of Interest

No potential conflict of interest was reported by the authors.

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