Treatment and Reuse of Black Water by Novel Energy-saving Shaft/Anaerobic /Anoxic/ Aerobic (S/A/A/O) System

A Novel Energy-saving Shaft/Anaerobic /Anoxic/ Aerobic (S/A/A/O) System for black water *Shaohong* You¹, *Qingjun* Zhang², *Lili* Ma^{1*}, *Mingze* Xu³ and *Hua* Lin¹

¹Guangxi Key Laboratory of Environmental Pollution Control Theory and Technology, Guilin University of Technology, Guilin 541004, China

²Liaoning urban construction design institute Co., LTD, Shenyang 110168, China

³Shenyang Agricultural University, Shenyang110866, China

Abstract: In this study the novel integrated anaerobic/anoxic/aerobic (A/A/O) and shaft aeration process system which could enhance the nutrient removal efficiency of wastewater with a low carbon nitrogen ratio (C/N) was investigated. Several dissolved oxygen (DO) ratios (1.0-2.0, 2.0-3.0, 3.0-4.0 mg/L) were applied in order to obtain more knowledge on the biological nitrogen and phosphorus removal performances. The experiment was carried out on a lab-scale Shaft-Anaerobic-Anoxic-Aerobic (S/A/A/O) wastewater treatment system. The average removal efficiencies of the total organic carbon, total nitrogen and phosphorus were 84.0%, 82.0% and 93.7%, respectively. The result showed that the proposed system was promising for the treatment of wastewater with a low C/N ratio because that in this system nitrification and denitrification happened simultaneously. Besides, the system had an automatic return system and its floor area was small, which made it energy-saving.

1 Introduction

It is widely acknowledged that the biological nutrient removal (BNR) system was suitable for the wastewater treatment plants nowadays because it can remove nitrogen and phosphorus simultaneously and has an economic advantage and a good flexibility[1]. The Anaerobic/Anoxic/Aerobic (A/A/O) process has been famous for its ability to remove nitrogen and phosphorus at the same time. However, this process still has some main operational problems [2, 3]. Firstly, the circulation pumps are not very energy efficient. What's more, traditional composting systems cover large areas and diffuse foul smell. Secondly, the system has some conflicts between the sludge *Corresponding author: 2006025@glut.edu.cn retention time (SRT) and polyphosphate accumulating organisms (PAOs). Thirdly, in the anaerobic area the denitrifiers and PAOs compete for the external carbon source, while the phosphorus released is inhibited by NO_3^- -N in the return sludge. Finally, the nitrogen and phosphorus removal rate is limited by the low C/N ratio of influent [3, 4].

However, black water (or toilet wastewater) is generally low in the C/N ratio and the discharge of one ton black water can pollute 220 tons clean water [5]. Nevertheless, the black water often lacks proper treatment before going to the wastewater treatment plants, which may cause serious problems. Therefore, it is of great importance to conduct research on technologies for black water treatment with higher efficiencies and lower costs [6]. The aerobic treatment of black water for recycling from toilet flushing is a promising alternative method. Membrane bioreactor (MBR) is one of the technologies to treat toilet wastewater, but this process has a high-energy consumption. Besides, cleaning and maintenance of the membrane is rather complicated [7, 8].

Therefore, it is a challenge to obtain sludge operation process with lower energy consumption and operation cost to meet the strict discharge standard. In order to solve the problems of traditional methods mentioned new above, energy-saving а Shaft/Anaerobic/Anoxic/Aerobic (S/A/A/O) system for black water treatment and recycling was proposed. The novel system, integrating S/A/A/O has several substantial advantages. Firstly, this process configuration makes sludge and mixed liquid fully automatic reflow back, which greatly save the energy of operation. In addition, it occupies smaller areas and diffuses no foul smell, so it is very reasonable to be used in residential areas. Secondly, simultaneous nitrification and denitrification (SND) that occurs in integrated anoxic/aerobic volume of S/A/A/O is a major asset. For this reason, SND is the most efficient process which is favorable for the treatment of low carbon wastewater [9, 10]. Thirdly, instead of the anaerobic zone NO₃-N is transferred to the anoxic area to guarantee the anaerobic environment for phosphate release [11], which also avoided the competition between denitrifiers and PAOs for external carbon source in the anaerobic zone. Finally, large amount of TOC in black water with a low C/N ratio is used in the anaerobic zone of S/A/A/O reactor. which is beneficial for the nitrification and then stimulate the growth of denitrifying polyphosphate accumulating organisms (DPAOs) which are capable to use excess NO₃⁻-N as electron acceptors. Therefore, the proposed process is promising and has a lot of advantages including removing nitrogen and phosphorus at the same time [12].

In this research, the automatic return systems of nitrate and sludge were investigated due to its good economical advantage in S/A/A/O system. The effects of DO which is relative to the nitrate recycling ratio on the nitrogen and phosphorus removal effecincy of the system was observed by treating real black water. Simultaneously, the energy consumption as well as the operational cost of the S/A/A/O process was analyzed.

To the best of our knowledge, this study is the first academic report about treatment and reuse of black water with S/A/A/O process.

2 Materials and methods

2.1 Experimental system

Fig.1 shows the new energy-saving S/A/A/O system. The working volume of the reactor was 90 L and it was made of plexiglass. The main body of this system was mainly composed of four parts: anaerobic zone, anoxic zone, aerobic zone, and a sedimentation pond with a working volume ratio of 1:1:3:1. For the septic tank, the raw black water went through an adjustment tank, and then entered the anaerobic zone, anoxic zone, and aerobic zone in series. In the aerobic zone, air was provided by a diffuser attached in the middle part of the reactor. The concentration of dissolved oxygen (DO) in the aerobic zone was controlled by a controller.

The nitrate flowed back to the anoxic zone by pushing downstream. Mixed flows in the anoxic zone were achieved by the plug-flow stirrer mounted at the bottom of reactor and mixed liquor of aerobic zone flowed to the sedimentation pond. In this part, some excess sludge went back automatically to the anaerobic zone through a back-flow hole, because the liquid level of the mixed flow with gas-liquid state is higher than that in the anaerobic zone, and the density of sludge is higher than that of liquid. Simultaneously, the rate of flow could be controlled by regulating the back-flow hole. The liquid supernatant was taken from the sedimentation tank and then flowed to the reclaimed water tank. The sedimentation tank could also be separated with the primary reactor, and the plug-flow stirrer could be replaced by upward diffusers with low ventilation for objective cause.



Fig.1. Schematic diagram of S/A/A/O biological system

2.2 Wastewater source

The wastewater used was taken from the residential area of Guilin University of Technology in Guilin, China. The main characteristics of the influent were summarized in Table 1.

Table 1. Main characteristics of the influ
--

Parameter	Range	Average
TOC/(mg/L)	169.0-93.5	131.3
TN/(mg/L)	107.0-65.4	86.2
NH4 ⁺ -N/(mg/L)	106.0-57.8	81.9
TP/(mg/L)	8.1-16.7	12.4
рН	8.61-7.26	7.93
T/°C	26.0-17.8	21.9

2.3 Analytical methods

All the samples were analyzed after filtrated by the 0.45 μ m filter paper. TOC and TN were measured using Multi N/C 3100 (Jena, Germany). NO₂⁻⁻N, NO₃⁻⁻N and PO₄³⁻⁻P were analyzed using Ion Chromatography System ICS-2100 (Dionex, America). DO was monitored by Dissolved Oxygen Meter AZ8403 (Hengxin, Taiwan). PH and temperature were detected, respectively by pH meter PB-10 (Sartorius, Germany) and online using probes. TP, NH₄⁺⁻N,

MLSS and Sludge Volume Index (SVI) were analyzed based on Standard Methods APHA (APHA/AWWA/WEF, 2005).

2.4 Calculation of the nitrogen removed through

SND in S/A/A/O process

The amount of nitrogen removed through SND process and the SND efficiency could be calculated according to Eq. 1 and 2, respectively.

$$N_{SND} = N_{influent} - N_{denitrification} - N_{assimilation} - N_{effluent}$$
(1)

$$SND_{efficiency} = \frac{N_{SND}}{N_{inf \ luent}}$$
(2)

Where N_{SND} , $N_{denitrification}$ and $N_{assimilation}$ are, the nitrogen removed by SND process, denitrification process and biomass assimilation process, g N/d. $N_{influent}$ and $N_{effluent}$ are the nitrogen in the influent and effluent, gN/d, respectively [13].

2.5 Calculation of anoxic P balance concentration

in S/A/A/O process

Based on material balance, anoxic P balance concentration (U, mg/L) could be calculated according to Eq. 3:

$$U = \frac{P_a \times (1+R) + P_b \times R}{1+R+r}$$
(3)

Where *R* and *r* is the sludge and nitrate recycling ratio, respectively; P_a is the PO₄^{3–}–P concentration in the effluent of the last anaerobic zone; P_b is the PO₄^{3–}–P concentration in the effluent of the last aerobic zone[14].

2.6 Operational conditions

The operational conditions which were chosen in the whole experimental period were presented in Table 2.

Items	Parameter	Value
HRT (h)	Hydraulic retention time	8
SRT (day)	Sludge retention time	10
Qin (L/day)	Influent flow	180
рН	Hydrogen ion concentration	7.3-8.6
DO _{ana} (mg/L)	Dissolved oxygen in the anaerobic zone	< 0.2
DO _{ano} (mg/L)	Dissolved oxygen in the anoxic zone	<0.5
DO _{ae} (mg/L)	Dissolved oxygen in the aerobic zone	1.0-2.0, 2.0-3.0, 3.0-4.0
MLSS (mg/L)	Mixed liquid suspended solids	3000-4000
SVI (mL/g)	Sludge volume index	60-110

Table 2. Operational conditions used in experiment

3 Results and discussion

At the end of the starting-up period, the S/A/A/O system was continuously operated until the removal efficiencies of TOC, TN, NH₄⁺-N and TP reached 83.8%, 76.6%, 87.3% and 82.1%, respectively.

3.1 Evolution of DO, Nitrogen, Phosphorus and

TOC in S/A/A/O system

Details of the variations in the three processes (DO at level of 1.0-2.0, 2.0-3.0, 3.0-4.0 mg/L) are described in Fig. 2. In the anerobic and anoxic zones, DO might be at 0.1–0.2 and 0.2–0.5 mg/L, respectively, whereas 1.0-4.0 mg/L of DO could be controlled around the aerobic zone of S/A/A/O. In this case, the optimum DO concentrations could make sure that the nitrogen and phosphorus removal processes worked in the corresponding zone.

It also indicated that the oxidation amount of NH_4^+ -N was even higher than the NO_3^- -N and NO_2^- -N produced in the aerobic zone at the three DO levels. The nitrogen species balance was also analyzed, which pointed that the SND process happened in the aerobic zones, especially at low DO levels. For the reason that the S/A/A/O system didn't have an absolutely separate anoxic volume, this reactor owned facultative zone with uneven DO concentrations. Higher MLSS was also favorable to the establishment of SND process. SND generally does not tend to be

sustained continuously in the conventional activated sludge due to the fact that the filamentous bacteria are active at a low DO concentration [10], while alternating anaerobic-anoxic-aerobic S/A/A/O can inhibit the growth of filamentous bacteria that will harm the settling properties and system stability [15]. Therefore SND can be sustained in the S/A/A/O under low DO levels and it can enhance the nitrogen removal efficiency.

The variable occurrence of anoxic P uptake in the S/A/A/O system was observed in this investigation by material balance calculation, $PO_4^{3-}P$ concentration reduction of anoxic area occupied, about 34.6%, 37.9% and 41.8% of the total $PO_4^{3-}P$ uptake , respectively (DO at level of 1.0-2.0, 2.0-3.0, 3.0-4.0 mg/L). The key factor which will influence the occurrence of DPAOs and the anoxic P-uptake was that there should be more than enough nitrate that can satisfy the denitrification activity of ordinary heterotrophic organisms (OHOs) [4]. Obviously the nitrate load in the anoxic zone seemed more likely to be achieved in the S/A/A/O reactor.

Approximately 60% of TOC was consumed in the anaerobic zone, and the majority of the carbon source in the influent was firstly used for storage as poly-hydroxy –alkanoate as the electron donor in the anaerobic zone. It was often stored by the denitrifying polyphosphate accumulating bacteria which was ready for absorbing phosphorus when treating wastewater with a low C/N ratio [16, 17]. Furthermore, the C/N ratio of supernatant decreased before. The wastewater flew to the aerobic zone. It was considered to be an advantage for the nitrification process for that the TOC had a non-inhibitory effect. Therefore, the variation of TOC in the S/A/A/O reactor was beneficial for both nitrogen and phosphorus removal in the anoxic zone.



- **Fig.2a**. Evolution of DO, Nitrogen, Phosphorus and TOC in S/A/A/O system when the DO ratio of aerobic zone at 1.0-2.0 mg/L.
- **Fig.2b** Evolution of DO, Nitrogen, Phosphorus and TOC in S/A/A/O system when the DO ratio of aerobic zone at 2.0-3.0 mg/L.
- **Fig.2c** Evolution of DO, Nitrogen, Phosphorus and TOC in S/A/A/O system when the DO ratio of aerobic zone at 3.0-4.0 mg/L.

3.2 Variations of TN and NH4+-N in the influent

and effluent and their removal efficiencies



Fig.3. Variations of TN and NH4+-N in the influent and

effluent and their removal efficiencies

As shown in Fig. 3, the removal efficiencies of TN and NH_4^+ -N were 81.9% and 90.0%, respectively. TN and NH_4^+ -N removals were also affected by the DO concentration. When the DO concentration was maintained at 2.0-3.0 mg/L, nitrification was relatively stimulated with an effluent TN and NH_4^+ -N of 12.5 and 5.7 mg/L, which almost reached the A standard of national wastewater discharge standard (GB18918-2002, China).

When the DO concentration was controlled at 2.0-3.0 mg/L, there was no NO₃⁻-N, and NO₂⁻-N detected in the effluent. And nitrogen compounds in the effluent were all at a very low level. Figure 2 showed SND was working well in this DO range, but the sludge became anoxic and even sometimes anaerobic when DO concentration got lower than 0.5 mg/L. In a relatively higher DO concentration the denitrifiers got inhibited and the heterotrophic aerobic bacteria became more active. Then with the presence of oxygen organic matter was consumed by bacteria rapidly, which made the denitrification process difficult[18]. Higher DO was not in favor of energy-saving. Nevertheless, the appropriate increase of nitrate recycling ratio with the increase of aeration rate increased the nitrate load supplied to the anoxic zone and improved the homogeneous distribution of microbial communities in the reactor. In the anaerobic environment a lot of TOC was consumed. Since the TOC had a non-inhibitory effect, this consumption was good for nitrification which resulted in the enhancement of TN removal [13]. Therefore, the optimal DO concentration for maximum efficiency of SND had a significant difference in this process.

3.3 Variation of TP in the influent and effluent and

their removal efficiency



Fig.4. Variation of TP in the influent and effluent and their removal efficiencies

Fig. 4 showed the phosphorus concentration in the influent and effluent as well as their removal efficiencies during the whole experimental period. The range of influent phosphorus concentration was 8.2 mg/L-16.7 mg/L. The average phosphorus concentration in effluent varied from 0.4 mg/L to 1.5 mg/L, and the corresponding removal efficiency was 93.7%. High TP removal efficiencies of 91.8%, 94.0% and 95.4% on average were obtained under DO level of 1.0-2.0, 2.0-3.0 and 3.0-4.0 mg/L respectively.

When treating the black water with a low C/N ratio, it is often effective to increase phosphorus removal ratio in the S/A/A/O process which often increase the N and P removal rate significantly. In the denitrifying phosphorus removal process, the same carbon source can be used for both N and P removal. Besides, the nitrate concentration in the anoxic reactor determined whether the DPAOs were active [19]. The denitrifying phosphorus removal was affected by the nitrate recycling ratio. It also explained the result that TP removal efficiency in anoxic zone had a bit increase when increasing the nitrate recycling ratio in Fig. 2.

3.4 Variation of TOC in the influent and effluent

and their removal efficiencies



Fig.5. Variation of TOC in the influent and effluent and their removal efficiencies

Fig.5 explained the TOC in the influent and effluent of the S/A/A/O and the TOC removal efficiencies in the whole experiment period. When the system started, the TOC removal efficiency varied from 77% to 87% and with an average of 82% when DO at level of 1.0-2.0 mg/L. After 30 days, with DO up to 2.0-3.0 mg/L, the removal efficiency of TOC varied from 78% to 91% with an average of 84%. Under the condition of DO 3.0-4.0 mg/L, the removal efficiency of TOC was relatively high and with an average of 86%, despite of the fluctuation of TOC from 99 to 131 mg/L in the influent.

In the S/A/A/O process, TOC removal is maintained at high levels and the DO which influenced the nitrate recycling ratio is an important operating parameter. The higher aeration rate could enhance the nitrate recycling ratio. Results showed that a higher DO level was conducive to the removal of TOC. It is suggested that a slightly higher percentage of TOC removal is caused by the denitrification of TOC uptake and the aerobic oxidization when increasing of nitrate recycling ratio [20].

4 Conclusions

The primary findings of this study are as below: (1) The S/A/A/O process with automatic return systems

could enhance the nutrient removal performance in treatment of low C/N ratio wastewater. (2) The average effluent concentrations of TOC, TN, NH_4^+ -N and TP were 18.5, 14.4, 5.8 and 0.8 mg/L, respectively. (3) The DO which influenced the nitrate recycling ratio is an important operating parameter.

This work was supported by National Natural ScienceFoundation of China (NO. 51868010), National Key R&DProgram ofChina (NO. 2018YFD0800704), GuangxiNaturalScienceFoundationProgram(NO.2018GXNSFAA138202) and the Guilin Science andTechnology Development Program(NO. 2016012004).

References

- F. Jie, T. Tao, Z. Jing, G.L. You, Desalination, 249, 822 (2009)
- J.A. Baeza, D. Gabriel, J. Lafuente, Process Biochemistry, 39, 1615 (2004)
- X. Wang, Y. Peng, S. Wang, J. Fan, X. Cao, Bioprocess & Biosystems Engineering, 28, 397 (2006)
- Y. Chen, C. Peng, J. Wang, L. Ye, L. Zhang, Y. Peng, Bioresource Technology, **102**, 5722 (2011)
- Y. Fan, G. Li, L. Wu, W. Yang, C. Dong, H. Xu, W. Fan, Process Biochemistry, 41, 1364 (2006)
- G. Zeeman, G. Lettinga, Water Science & Technology, 39, 187 (1999)
- A. Sofia, W.J. Ng, S.L. Ong, Desalination, 160, 67 (2004)
- H. Knerr, A. Rechenburg, T. Kistemann, T.G. Schmitt, Water Science & Technology A Journal of the International Association on Water Pollution Research, 63, 1247 (2011)
- S. Luostarinen, W. Sanders, K. Kujawa-Roeleveld, G. Zeeman, Bioresource Technology, 98, 980 (2007)
- S.M. Hocaoglu, G. Insel, E.U. Cokgor, D. Orhon, Bioresour Technol, **102**, 4333 (2011)
- H. Lee, J. Han, Z. Yun, Water Science & Technology A Journal of the International Association on Water Pollution Research, 59, 2093 (2009)

- J.Y. Hu, S.L. Ong, W.J. Ng, F. Lu, X.J. Fan, Water Research, 37, 3463 (2003)
- S. Ge, Y. Peng, S. Wang, J. Guo, B. Ma, Z. Liang, C. Xu, Bioresource Technology, 101, 9012 (2010)
- W. Zeng, L. Li, Y.Y. Yang, X.D. Wang, Y.Z. Peng, Enzyme & Microbial Technology, 48, 134 (2011)
- P. Madoni, D. Davoli, Bioresource Technology, 60, 43 (1997)
- F. Wang, S. Lu, Y. Wei, M. Ji, Journal of Hazardous Materials, 164, 1223 (2009)
- C.Y. Wu, Y.Z. Peng, C.L. Wan, S.Y. Wang, Journal of Chemical Technology & Biotechnology, 86, 461 (2011)
- Q. Meng, Journal of Environmental Sciences, 20, 933 (2008)
- Z.R. Hu, M.C. Wentzel, G.A. Ekama, Water Science & Technology A Journal of the International Association on Water Pollution Research, 43, 251 (2001)
- Y.M. Kim, H.U. Cho, D.S. Lee, D. Park, J.M. Park, Water Research, 45, 5785 (2011)