Sustainable Environment Research

RESEARCH

Open Access

Study on high-concentration activated sludge system for energy-efficient nitrogen removal in wastewater

Benfu Luo[1*], Yuhang Liu[1], Yiqiang Huang[2], Weiwei Huang[3], Qiang Chen[4], Yujing Yan[1], Haixing He[1], Xiang Zhou[5] and Jie Yu[1]

Abstract

Currently, there is an increasing emphasis on energy conservation and nitrogenous pollutant emission reduction, and conventional wastewater treatment processes can no longer meet the demand. Enhancing the reflux ratio of the mixed liquor suspended solids (MLSS) is a promising option to improve nitrogen removal in wastewater treatment. However, a high reflux ratio can lead to a significant carryover of dissolved oxygen (DO), which can negatively impact the denitrification process. Currently, eliminating the effects of DO remains a challenging area with high DO concentration inhibiting denitrification process. The high MLSS system can significantly reduce the impact of DO. Therefore, this study compares it with the conventional internal recirculation method in terms of pollutant removal and DO recovery. It explores the feasibility of using high MLSS system to enhance nitrogen removal in wastewater treatment while achieving energy savings, and calculates the potential energy savings achieved. At the same time, the biological tank reflux pump used by the air-lift pump exhibited more energy-saving advantages than the traditional mixture of liquid reflux pumps. This study focuses on wastewater treatment plants with poor denitrification performance, aiming to enhance denitrification efficiency. The results show that when the MLSS concentration is 8.0 g L^{-1} with the DO concentration 2.5 mg L^{-1}, the system removed 97% of biochemical oxygen demand at influent 200 mg L^{-1}, 86% of chemical oxygen demand (Cr method) at 350 mg L^{-1}, 94% of ammonia nitrogen at 35 mg L^{-1}, and 72% of total nitrogen at 45 mg L^{-1}. This study can significantly reduce operating costs. The air-lift pump facilitates the lifting of wastewater, it also supplies DO to the water, thereby reducing the need for aeration. Compared to traditional recirculation methods, this approach saves approximately 32% of DO, resulting in an effective recovery, which notably enhances energy savings. However, it is important to note that the small scale of the bioreactor used in this experiment does not fully capture the advantages in energy saving and management that come with the implementation of a high MLSS system.

Keywords High concentration activated sludge process, Denitrification, Reflux ratio, Dissolved oxygen, Energy saving and consumption reduction

*Correspondence:
Benfu Luo
kkllbbff@mail.xhu.edu.cn
Full list of author information is available at the end of the article

1 Introduction

Biological denitrification is an environmentally friendly process that reduces nitrate levels in water by converting nitrate into nitrogen gas [1]. While nitrification removes total Kjeldahl nitrogen, denitrification removes total nitrogen (TN). Currently, commonly used nitrogen removal processes include the A/O and AAO methods. The A/O process is designed solely for TN removal, while the AAO process can simultaneously achieve both nitrogen and phosphorus removal. However, as the demand for wastewater treatment continues to rise [2], the AAO process suffers from the problem that nitrifiers and phosphorus-accumulating organisms require different sludge retention times [3]. Typically, A/O biological contact oxidation processes use a non-recirculating flow operation mode to reduce construction costs and operational energy consumption. However, due to the lack of recirculation in the denitrification process, the quality of the effluent does not meet higher discharge standards, particularly concerning TN parameter [4].

To improve denitrification efficiency, various methods have been employed, among which the addition of external carbon sources is one of the most common and straightforward approach in wastewater treatment plants due to its simplicity and convenience [5]. However, increasing the use of external carbon sources leads to additional financial burdens, with limited returns on investment [6]. For instance, traditional AAO processes achieve only a 45–62% TN removal efficiency when treating municipal wastewater with a low carbon to nitrogen (C/N) ratio of 4.4 [7], resulting in a low cost-effectiveness ratio. Another approach to enhance denitrification efficiency is to increase the external nitrate reflux ratio (introduction of anoxic zone from aerobic zone), which can elevate the NO_3^- concentration [8], thereby promoting denitrification. Studies have shown that incorporating 30% sludge recirculation (from settling zone to aerobic zone) in activated sludge systems can significantly reduce nitrogen in treated effluent [9]. Higher reflux ratios enhance the contact between sludge and membrane bioreactor (MBR) [10], fostering microbial growth and reproduction, ultimately leading to improved TN removal efficiency. However, increasing the internal reflux ratio in existing biological treatment processes leads to higher operational energy consumption and can adversely affect the anoxic zone due to the carryover of dissolved oxygen (DO) in the reflux. Consequently, there are limitations to how much the internal reflux ratio can be increased, making significant breakthroughs in denitrification efficiency challenging.

The application of a high internal recirculation ratio within the biological tank significantly promotes pollutant removal compared to conventional internal recirculation. By increasing the internal recirculation ratio, the system's TN removal efficiencies can be enhanced; however, measures must be taken to mitigate the impact of DO carried by the mixed liquor recirculation on the anoxic zone. To address the issue of excessive dissolved DO in the return flow liquid under the denitrification process, the concept of combining high mixed liquor suspended solids (MLSS) system with a high return ratio technology has emerged. This approach not only mitigates the DO problem but also contributes to energy savings. The MLSS in existing activated sludge systems, both domestically and internationally, typically hover around 3 g L^{-1}. In contrast, high MLSS systems usually operate with an MLSS of over 4 g L^{-1} [11], which supports a greater abundance of microorganisms that can effectively consume excess DO. Additionally, a significant phenomenon of simultaneous nitrification–denitrification (SND) occurs in high concentration activated sludge reactors. SND offers several advantages, including high nitrogen removal efficiency, reduced space requirements, and lower nitrogen removal costs per unit [12]. It can lead to approximately 25% savings in aeration volume and around 30% reduction in carbon demand [13]. As a result, the demand for external addition of organic matter is not high. Additionally, the microbial growth rate can be adjusted through the control of aeration rates in relation to the Food-to-Microorganisms ratio. Studies have shown that increasing the sludge concentration in the system not only prevents the disruption of the anoxic environment by DO but also enhances the removal efficiencies of biological oxygen demand (BOD), chemical oxygen demand (COD_{Cr}), and ammonia. When the MLSS level in the reactor is high, the TN removal efficiencies are also elevated, with the SND phenomenon becoming more pronounced [14]. High MLSS levels lead to uneven DO distribution, establishing aerobic and anaerobic microenvironments within microbial aggregates (such as flocs and biofilms). This allows for the simultaneous growth and proliferation of nitrifying and denitrifying bacteria [15]. Furthermore, in this experiment, an air-lift pump was utilized, which not only enhances the internal recirculation ratio but also improves the removal of TN [16]. Meng et al. [17] demonstrated that the simultaneous SND process can be achieved in an air-lift reactor when treating synthetic wastewater with a DO level of 1.0 mg L^{-1}, showcasing an excellent compatibility with the high MLSS system.

The use of the high MLSS system to increase the recirculation ratio in wastewater treatment not only demonstrates significant effectiveness in nitrogen removal but also excels in the removal of other pollutants and in energy conservation. For example, the enhanced rural A/O biological contact oxidation reactor developed by

Zheng et al. [4] operates under both non-recirculation and air-lift recirculation modes. The air-lift recirculation process significantly improves the removal efficiencies of COD (increasing from 75 to 85%) and SS (rising from 91 to 97%). It is evident that the advantages brought by a high recirculation ratio are considerable. In the one-year continuous operation, the pilot-scale high MLSS system was proven to be able to achieve stable and excellent nitrogen and phosphorus removal of low-temperature municipal sewage [18]. Furthermore, the activated sludge and synergistic effect of biofilm has considerable potential in removing aniline and simple aromatic containing nitrogen compounds, as well as reducing energy consumption [19]. Compared to previous studies, this research innovatively applies the high MLSS system to a large-scale recycling technology, resulting in a significant enhancement of DO recovery and a reduction in resource consumption.

To address these issues, this study explores the application of high MLSS system under high internal recirculation ratios, comparing it with conventional internal recirculation in terms of progress made in nitrogen removal and energy conservation. The objectives of this research are: (1) Investigating the effectiveness of pollutant removal following the adoption of high MLSS system; (2) Monitoring DO levels enables a quantitative assessment of the recovery efficiency of DO when compared to conventional internal recirculation methods; and (3) Calculating operational energy consumption for both high recirculation ratio and conventional internal recirculation modes.

2 Materials and methods

2.1 Test water quality

The wastewater for this experiment was prepared onsite according to the water quality outlined in Table 1. The chemicals used for wastewater preparation include glucose, urea, and potassium dihydrogen phosphate for microbial growth. The wastewater composition used in this experiment does not represent the situation of the actual wastewater, but can provide some reference value. The wastewater will be mixed in a preparation tank, with thorough stirring several times to ensure a uniform mixture. The prepared wastewater will then be gravity-fed through DN25 hoses into the biological reactor's pre-anoxic zone, anaerobic zone, and anoxic zone, respectively. Sludge return is introduced into the pre-anoxic zone from the settling tank at the end of the biological reactor via an air-lift device.

2.2 Test setup

The main design parameters of the biological reactor are as follows:

Design flow: 3.0 m^3 d.$^{-1}$

Structural dimensions: L × B × H = 2.0 × 1.3 × 1.0 m.

Activated Sludge Concentration: 8.0 g L^{-1} in large proportion reflux test; In the conventional internal reflux ratio test, it was 4.0 g L.$^{-1}$

Total solids retention time (θ) = 14.7 d.

Sludge cultivation: The cultivate of sludge in this experiment was carried out by inoculation culture method. The inoculated sludge was taken from the return sludge of the second settling tank of the nearby sewage plant. The sludge is added to the biological reactor for inoculation and cultivation for seven days when the design concentration is reached, the operation is then started.

Effective water depth: 0.9 m.

Hydraulic retention time (HRT) = 16.2 h (Among them, the pre-anoxic zone was 2.0 h, with the anaerobic zone 1.5 h, the anoxic zone 4.2 h, and the aerobic zone 8.4 h).

Sludge return ratio: R = 100%

Reflux ratio in mixed liquid: 800–1200% in large proportion reflux test; 200–300% in conventional internal reflux ratio test.

Sedimentation zone: the average surface load is 0.32 m^3 m^{-2} h^{-1}, and the HRT is 2.8 h.

The parameters of the air pick-up pump are as follows:

The submersion ratio: 0.8

Lifting pipe diameter: DN30 mm.

The above design parameters were calculated based on a scaled-down version of the actual wastewater treatment plant size.

The test device is shown in Fig. 1, and the process flow diagram is shown in Fig. 2.

2.3 Main equipment materials

The main equipment and materials of this stage of the test are shown in Table 2.

2.4 Test protocol

2.4.1 Experimental studies on the effect of contaminant removal

The experimental tests were operated in two modes—high internal reflux and conventional internal reflux—each for

Table 1 Feed water quality

The name of the contaminant	BOD	COD_{Cr}	SS	TN	TP	NH_3-N	pH
Design values (mg L^{-1})	200	350	240	45	5	35	8.5

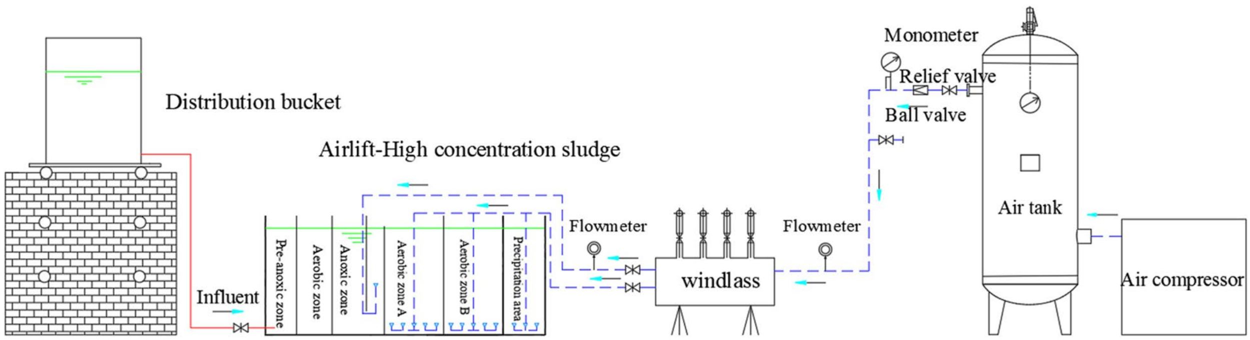

Fig. 1 Schematic diagram of test device

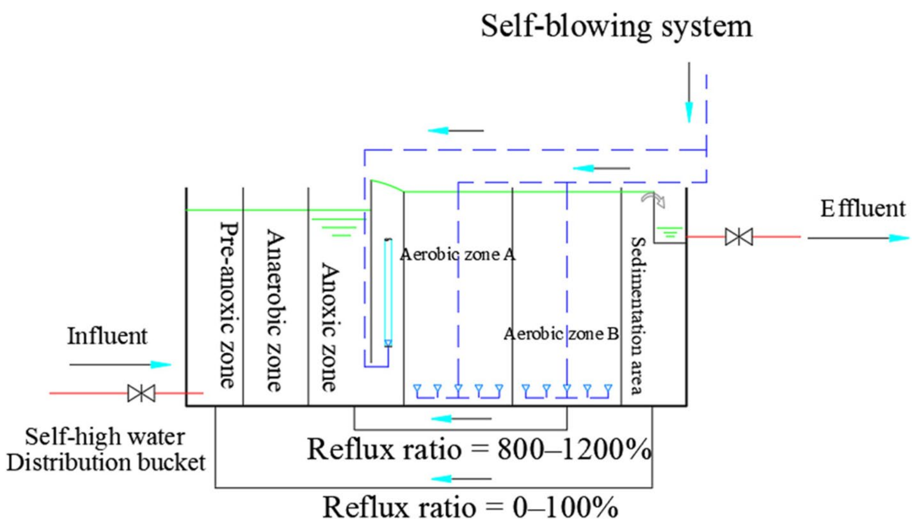

Fig. 2 Process flow diagram

Table 2 Test main equipment and material list

Serial number	Equipment/Materials	Model/Specification	Remark
	(1) Experimental equipment		
1	Screw air compressor	1.5 m^3 min^{-1}, 7.5 kW, P = 1.0–0.6 MPa	It is used to transport gases
2	Glass rotameter gas flow meter	LZB-3, 0.6–6 m^3 h^{-1}	It is used for air flow measurement, supporting pipe fittings
3	DO meter	MP551 type	It is used for the measurement of DO in reactors
4	ORP measuring instrument	ORP-422 type	It is used for the measurement of reactor ORP
5	Windbag (Air Regulator)	DN 400 mm	It is used to regulate the gas flow
6	Tubular aerators	L = 1.0 m, DN 50 mm	It is used for aeration in aerobic zones
7	Biological reactor (cast iron)	L × B × H = 2.0 × 1.3 × 1.0 m	It is used for activated sludge reactions
	(2) Chemicals used		
1	Cultured glucose	/	It is used for sewage preparation and carbon source dosing
2	Urea	/	It is used in the preparation of wastewater
3	Potassium monobasic phosphate	/	It is used in the preparation of wastewater
4	H_2SO_4	/	pH adjustment
5	NaOH	/	pH adjustment

a duration of 14 d. During a single HRT test cycle, water samples will be taken at 2-h intervals. The samples will undergo water quality testing to calculate the removal efficiencies of various pollutants, and pollutant removal trends will be plotted. Additionally, a comparative analysis will be conducted on the trend curves from the two operational modes.

2.4.2 Experimental study of DO recovery

In the high reflux ratio operation mode, the initial DO concentration of the test was monitored. The test protocol is as follows:

a. Simultaneously activate the aeration pump and the aeration tubing of the biological tank, monitoring the DO concentration in the biological tank. Adjust the aeration flow to maintain the DO level at 2.5 mg L^{-1} and record the flow rates for each aeration tube at this time;
b. Close the pump valve of the aeration tubing, and adjust the valve of the biological tank's aeration system to keep its flow rate constant. Monitor the DO concentration in the biological tank for 15 min, recording the measurements and calculating the average value, which will represent the DO contribution from the biological;
c. Subtract the DO contribution from the biological tank's aeration from the target DO level in the tank to determine the contribution of the aeration pump to the DO levels. This will allow for the calculation of the DO recovery efficiency attributed to the aeration pump.

2.4.3 Experimental studies on energy costs

The experiment will operate for 14 d under both high reflux ratio and conventional internal reflux ratio modes, maintaining the DO concentration in the biological tank at 2.5 mg L^{-1}. During this period, the average aeration flow rate for each operating mode will be monitored and recorded. The total aeration volume for both modes will be calculated, allowing for the assessment of the operational energy consumption for each operating mode.

2.5 Test items and methods

The water quality analysis methods used in the test were all determined according to the water and wastewater analysis methods of the State Environmental Protection Administration, and the specific methods are shown in Table 3.

2.6 Energy consumption calculation method

The daily power consumption (kWh) of the air compressor is:

$$P_{consume} = \frac{PQT}{q} \tag{1}$$

where Q (m^3 h^{-1}) is the average ventilation volume, T (h) is the ventilation time, q (m^3 min^{-1}) is the exhaust volume of the air compressor, and P (MPa) is the power of the air compressor.

3 Results and discussion

3.1 Comparative analysis of the removal efficiency of BOD and CODcr

The experiment will be conducted under two modes: high internal reflux (Operation Mode A) and conventional internal reflux (Operation Mode B), each lasting for 14 d. During a single HRT test cycle, water samples will be taken every 2 h during the operation and subjected to water quality testing. Based on the water quality data, removal efficiency for COD_{Cr} and BOD under both operating modes will be plotted.

In the two operating modes described above. As shown in Fig. 3, the influent COD concentration for Mode A ranged from 333 to 362 mg L^{-1}, with an

Table 3 Test main equipment and material list

Number	Measurement metrics	Unit	Measurement method	Major instrument brands
1	TN	mg L^{-1}	Potassium persulfate oxidation-ultraviolet spectrophotometry	Hach DR3900 spectrophotometer
2	Ammonia nitrogen	mg L^{-1}	Nessler's reagent photometry	Hach DR3900 spectrophotometer
3	COD	mg L^{-1}	Potassium dichromate method	
4	BOD	mg L^{-1}	Dilution inoculation method	
5	DO	mg L^{-1}	Portable DO meter	Shanghai Sanxin MP551 type
6	pH	-	Portable DO meter	Shanghai Sanxin MP551 type
7	Temperature	℃	Portable DO meter	Shanghai Sanxin MP551 type
8	Ventilation	m^3 h^{-1}	Air flow meter	Ralda LZB type
9	MLSS	mg L^{-1}	Gravimetric method	

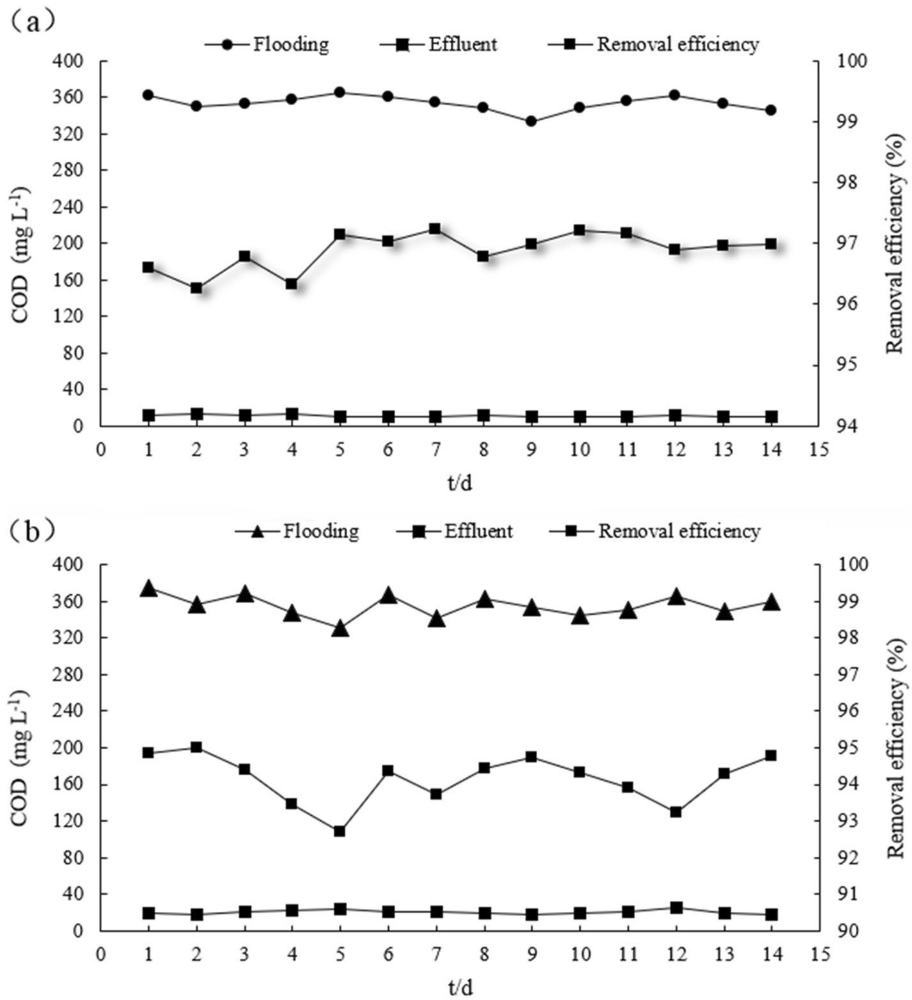

Fig. 3 The removal effect of operation mode A (**a**) and B (**b**) on COD

average value of 353 mg L^{-1}. for Mode B, the influent COD concentration ranged from 331 to 374 mg L^{-1}, with an average of 355 mg L^{-1}. All of them meet the Class A discharge standard (75 mg L^{-1}) specified in the"Standards for Pollutant Discharge from Urban Sewage Treatment Plants."As shown in Fig. 4, the influent BOD concentration for Mode A ranged from 198 to 213 mg L^{-1}, with an average value of 204 mg L^{-1}. the Mode B showed a concentration range of 186 to 214 mg L^{-1}, with an average value of 202 mg L^{-1}. All of them meet the Class B discharge standard (45 mg L^{-1}) outlined in the"Standards for Pollutant Discharge from Urban Sewage Treatment Plants."The comparative graphs of the two modes clearly indicate that Operational Mode A outperforms Mode B in the removal efficiency of both COD and BOD. This is particularly evident in the removal efficiencies of these two pollutants (Mode A, (achieves average removal efficiencies of 96% for COD and 85% for BOD, Mode B's efficiencies of 94 and 81%). As can be seen from Fig. 5, the difference between mode A and mode B is significant. One of the main reasons for this is the high sludge concentration in Mode A (8 g L^{-1}). Li et al. [20] found that using high MLSS system resulted in sludge concentrations exceeding 6600 mg L^{-1}, significantly surpassing the traditional AAO process range of 3000 to 4500 mg L^{-1}. The formation of a substantial biofilm from the high sludge concentration can effectively biodegrade pollutants, leading to a higher COD removal efficiencies [21]. Therefore, the elevated sludge concentration may be a key factor contributing to the system's efficient removal of pollutants. Additionally, the high internal recirculation technology employed in this experiment plays a crucial role in enhancing nitrogen removal. For typical municipal wastewater, the removal of COD_{Cr} and BOD occurs in tandem, as they are generally utilized by

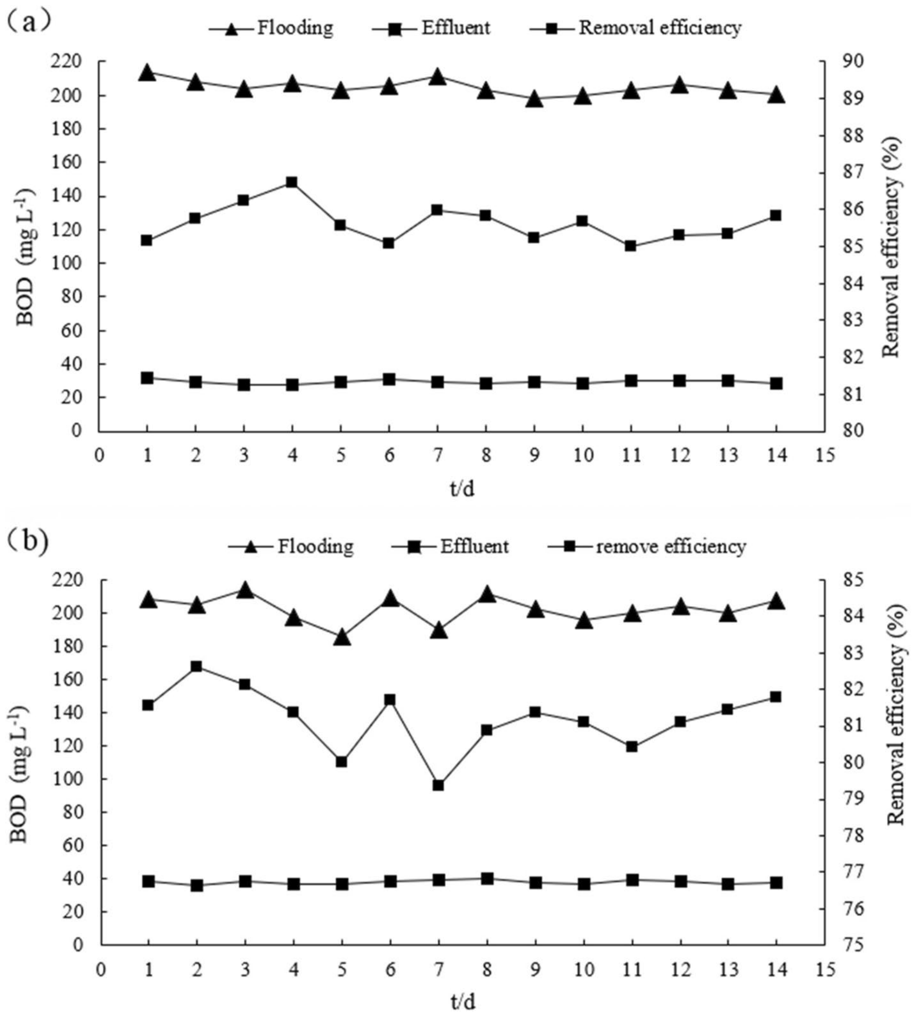

Fig. 4 The removal effect of operation mode A (**a**) and B (**b**) on BOD

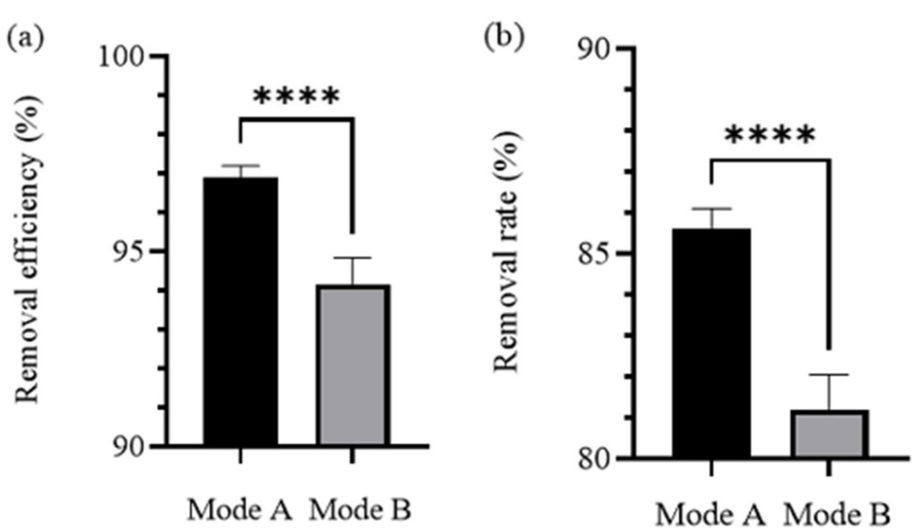

Fig. 5 Significant analysis of COD (**a**) and BOD (**b**) removal efficiencies between mode A and mode B

microorganisms as a carbon source necessary for their growth. The denitrification process involves two main mechanisms: one is the conversion of nitrate to N_2, and the other is the anaerobic oxidation of ammonia (anammox) [22]. Furthermore, during the high recirculation of mixed liquor within the bioreactor, a nitrate-rich matrix forms at the bottom of the reactor [23]. This provides a source of nitrate for denitrification in the anaerobic zone, enhancing the microorganisms'uptake of organics. Research has shown that when the HRT is set to 4 h, the physical removal efficiency of COD significantly increases (by 8–20%) [24], which may also be a contributing factor.

3.2 Analysis of the removal effect of ammonia

The ammonia removal under the two operation modes are illustrated in Fig. 6.

In the two operational modes, the influent ammonia nitrogen concentration as shown in Fig. 6, for Mode A ranged from 33 to 37 mg L^{-1}, with an average of 35 mg L^{-1}. for Mode B, it ranged from 32 to 38 mg L^{-1}, with an average of 35 mg L^{-1}. All of them comply with the Class A discharge standard (10 mg L^{-1}) specified in the"Standards for Pollutant Discharge from Urban Sewage Treatment Plants."Additionally, the removal curves for ammonia nitrogen clearly indicate that Mode A achieves higher removal efficiencies compared to Mode B, with average removal efficiencies of 94 and 91%, respectively. As can be seen from Fig. 7, the difference between mode A and mode B is significant. In the bioreactor, the removal of ammonia primarily relies on nitrifying bacteria, which require longer reproduction cycles, extended sludge ages, and sufficient reactor volume, thus necessitating consideration of enhanced nitrification. For typical domestic wastewater, high removal efficiencies of ammonia can be achieved under adequate aeration conditions.

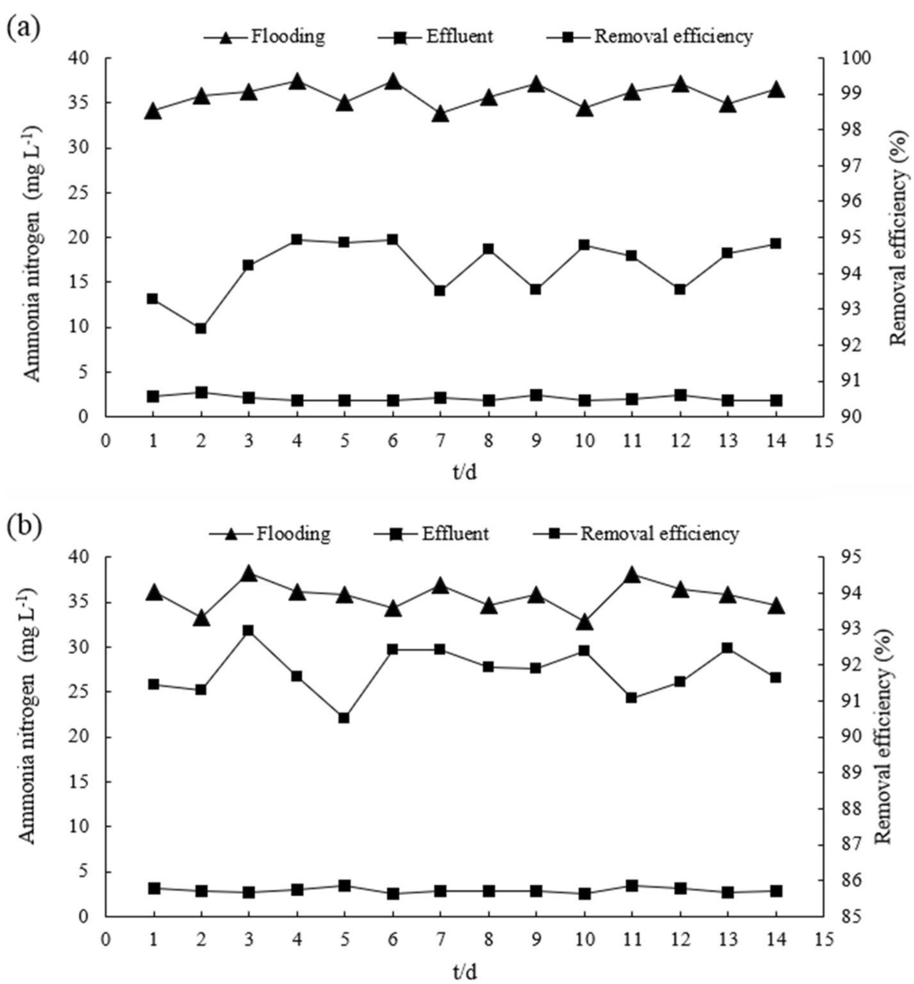

Fig. 6 The removal effect of operation mode A (**a**) and B (**b**) on ammonia nitrogen

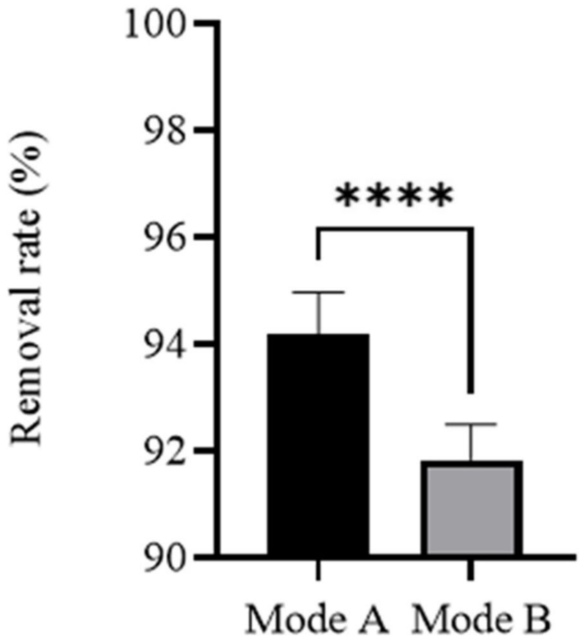

Fig. 7 Significant analysis of ammonia nitrogen removal efficiencies between mode A and mode B

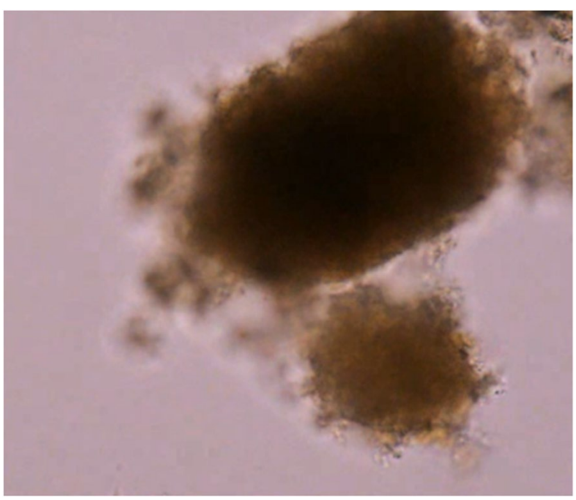

Fig. 8 Bacterial colloid morphology of a high concentration activated sludge system

Based on the two operational modes employed in this experiment, the elevated sludge concentration in Mode A positively contributes to the removal of ammonia. Research has shown that aerobic granular sludge with a distinct multilayer structure in high-concentration activated sludge reactors possesses a dense structure and high biomass concentration, resulting in superior treatment capacity, rapid settling, and a diverse microbial community [25]. As shown in Fig. 8, the high MLSS system contains some flocs that are large in volume and densely structured. Due to the nature of these flocs, the transfer of oxygen within them faces significant resistance, resulting in a gradient of DO. There are anaerobic zones within the flocs, creating microenvironments that are conducive to the activity of denitrifying bacteria. This concentration gradient of DO facilitates the coexistence of autotrophic nitrifying bacteria and heterotrophic denitrifying bacteria [26], thereby enhancing the removal efficiencies of ammonia. Additionally, the high sludge concentration limited oxygen transfer, creating multiple zones where nitrifiers and denitrifiers can coexist. In these zones, the DO levels are sufficient for nitrification to occur in the outer layer of the aggregates, while the interior of the aggregates provides the anoxic conditions necessary for denitrification. This arrangement effectively promotes the SND process [27]. This is the primary reason for the difference in ammonia removal efficiencies between Mode A and Mode B.

3.3 Analysis of the removal effect of TN

The test data were sorted out and analyzed, and the change curves of TN removal under the two operation modes were plotted.

The influent conditions for the two operational modes were as follows: As shown in Fig. 9, Mode A had a range of 44 to 48 mg L^{-1} (average of 45 mg L^{-1}); Mode B ranged from 43 to 47 mg L^{-1}, averaging 45 mg L^{-1}. From the variation curves of the two models, it is evident that Model A demonstrates a significant advantage in nitrogen removal, achieving an average removal efficiency of 72%. The average discharge concentration is around 15 mg L^{-1}, which meets the Class A discharge standard (20 mg L^{-1}) set forth in the"Standards for Pollutant Discharge from Urban Sewage Treatment Plants."In contrast, Model B achieves only a 61% removal efficiency, with a discharge concentration that is very close to 20 mg L^{-1}. As can be seen from Fig. 10, the difference between mode A and mode B is significant. The notable difference in removal efficiencies between the two modes can primarily be attributed to the high recirculation ratio of mixed liquor and the elevated sludge concentration in Mode A.

To further investigate the reasons for the differences in removal efficiencies between the two modes, we increased the internal recirculation ratio of Mode B to 400 and 500%. Run for one cycle under two internal reflux ratios and take water samples at regular intervals for water quality testing. And analyze the impact of the 400 and 500% internal recirculation ratios on TN removal in Mode B. The water quality data will be organized, and the variations in TN removal efficiencies over

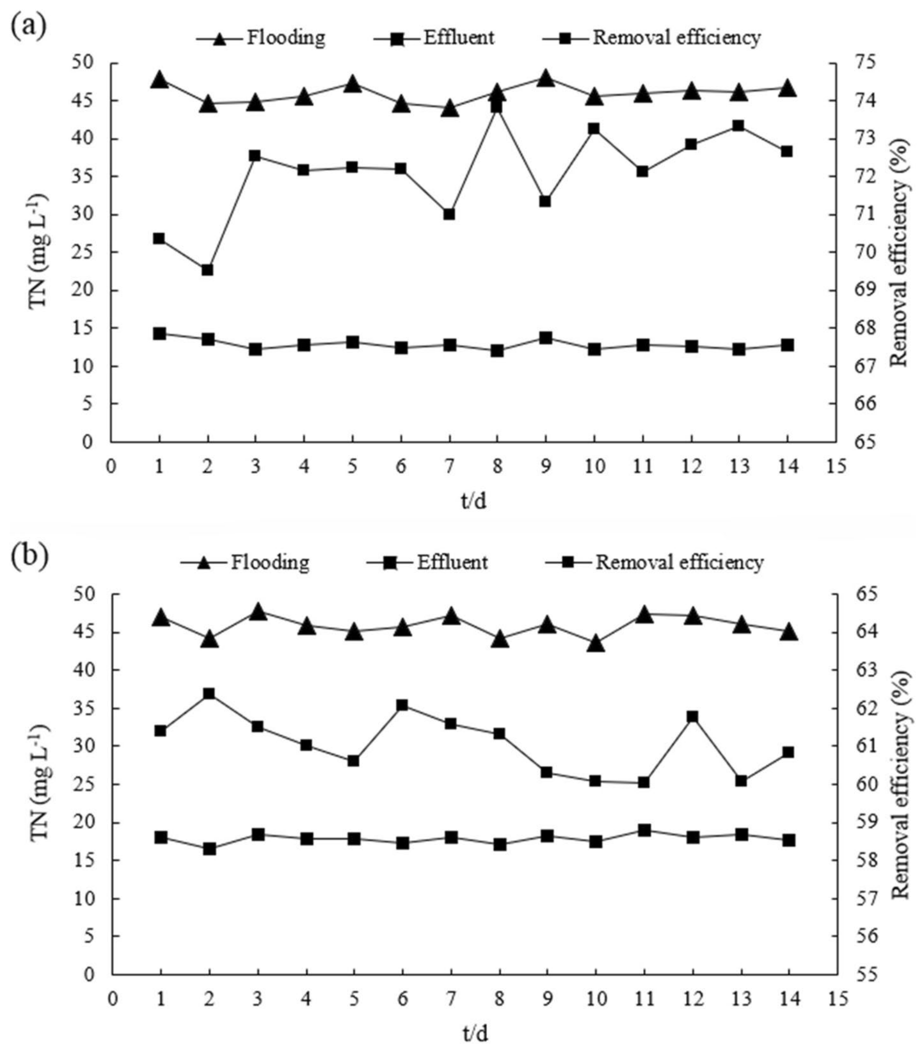

Fig. 9 The removal effect of operation mode A (**a**) and B (**b**) on TN

the operational cycle will be plotted for different internal recirculation ratios (see Fig. 11).

The influent TN concentrations for the two recirculation ratios were 44 mg L^{-1} for the 400% ratio and 45 mg L^{-1} for the 500% ratio. From the variation curves, it is evident that for Mode B (with the conventional internal recirculation ratio), an appropriate increase in the recirculation ratio can enhance the system's TN removal efficiency. Specifically, the TN removal efficiencies were 65% at the 400% recirculation ratio and 62% at the 500% ratio, both of which are slightly higher than the removal efficiency of 61% observed with the conventional recirculation ratio. Therefore, the reflux ratio is directly related to the removal of organic matter and nitrogen in anoxic-aerobic techniques [28], however, indiscriminately increasing the internal recirculation ratio does not lead to a continuous increase in TN removal efficiency; in fact, it can result in a decrease in the system's TN removal efficiency (The TN removal efficiency at the 400% recirculation ratio was 65%, while it dropped to 62% at the 500% ratio). To analyze the reasons for the results mentioned above, it is important to note that denitrification is a critical process in biological nitrogen removal. The availability of a carbon source and DO are significant factors that influence the denitrification process. A low C/N ratio can result in insufficient organic carbon during the denitrification process [29]. In this experiment, the wastewater had a BOD/TN ratio of 4.4, which is greater than 4, indicating that the organic carbon source is relatively abundant. Additionally, the use of multiple points for influent introduction in the biological reactor has increased the utilization of organic carbon sources. As such, the impact of the carbon source on biological nitrogen removal through denitrification in this study was limited. On the other hand, DO is one of the key factors influencing nitrate removal efficiency [30], as nitrate

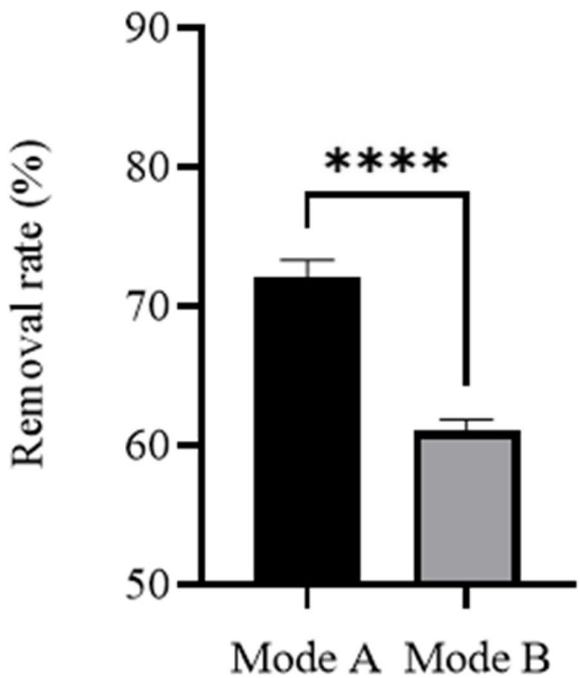

Fig. 10 Significant analysis of TN removal efficiencies between mode A and mode B

is a crucial component in the first stage of the denitrification reaction. Therefore, it can be speculated that the primary reason for the reduction in nitrogen removal efficiency associated with the increased recirculation ratio is the effect of DO on the denitrification process. To verify the aforementioned hypothesis, we monitored the DO concentration in the anoxic zone of Mode B under the operating conditions of 400 and 500% recirculation ratios. The monitoring protocol involved measuring the DO concentration in the anoxic zone every hour (averaging the values over a 15-min interval). The DO concentrations at the 400 and 500% recirculation ratios were designated as DO_1 and DO_2, respectively. We then compared DO_1 and DO_2 with the DO concentration in the anoxic zone of Mode A, which utilizes a high recirculation ratio, designated as DO_3. This comprehensive analysis aims to assess the impact of increased recirculation ratios on denitrification caused by changes in DO levels. The monitoring data for DO_1, DO_2, and DO_3 were organized, and the variation curves were plotted; please refer to Fig. 12 for details.

From the variation curves, it can be observed that under the operating conditions of 400 and 500% recirculation ratios, the average DO concentration in the anoxic zone was 0.5 mg L^{-1} when the recirculation ratio was 400% (DO_1), while it increased to 0.6 mg L^{-1} when the recirculation ratio was 500% (DO_2). Typically, the DO concentration in the anoxic zone should not exceed 0.5 mg L^{-1}, as higher levels can negatively impact the denitrification process. Reducing the aerobic DO concentration is beneficial for maintaining a low DO environment in the anoxic zone [31]. Therefore, the results indicate that DO is the primary reason for the reduction in nitrogen removal efficiency when increasing the recirculation ratio. An excessively high recirculation ratio leads to an increased DO concentration carried by the return nitrate, which can disrupt the operating conditions of the anoxic zone and subsequently inhibit the denitrification process. This also explains why it is

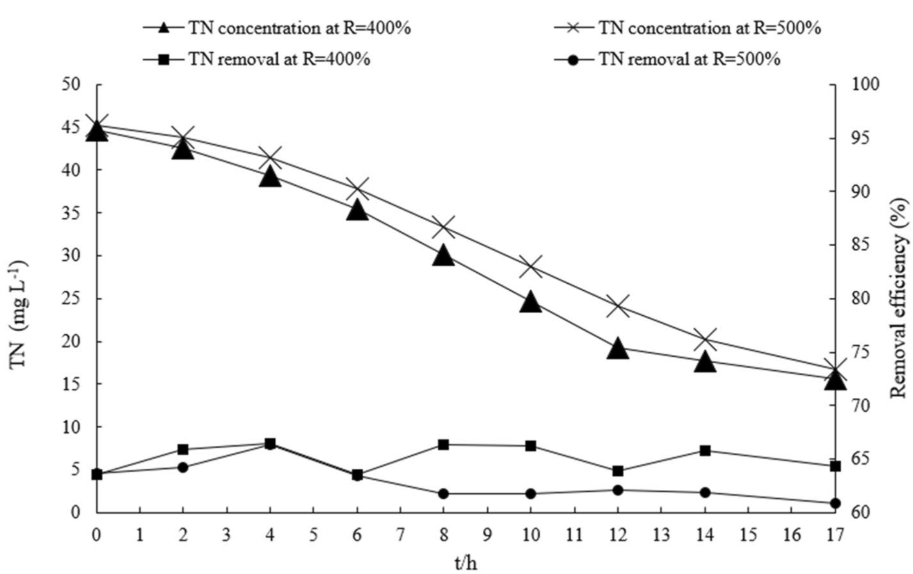

Fig. 11 Removal effect of mode B on TN under operating conditions of R = 400% and R = 500%

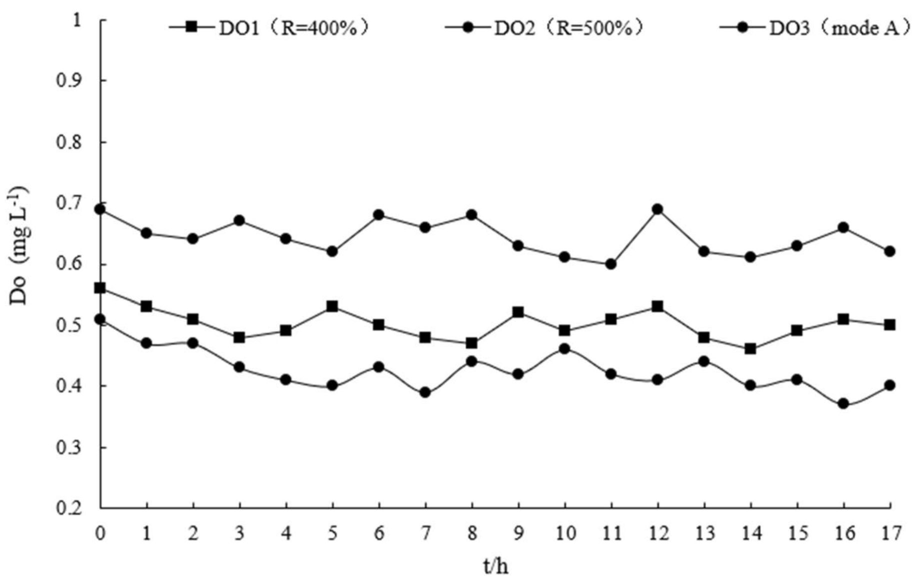

Fig. 12 Mean concentration of DO in anoxic zone under different internal reflux ratios

challenging to significantly increase the recirculation ratios in conventional biological treatment processes. In engineering applications, when the recirculation ratio exceeds 400%, oxygen removal measures are typically implemented. A common practice is to establish an oxygen removal zone (degasification zone) at the return end of the mixed liquor, with a HRT of approximately 0.5 to 1.0 h. This reduces the DO concentration before the mixture enters the anoxic zone, creating a low DO environment that is conducive to retaining inflow carbon sources and effectively removing TN [32]. In existing treatment processes, only wastewater treatment plants utilizing the MBR technology can achieve high recirculation ratios (above 700%). This is primarily due to the higher sludge concentration in MBR systems (which is 2 to 3 times greater than that of traditional processes). The elevated sludge concentration helps reduce the DO levels in the anoxic zone, thereby enhancing the denitrification efficiencies and improving the system's nitrogen removal capacity [33]. Moreover, a high sludge concentration can lead to an increase in the MLSS and the variety of organic substrates. Studies have shown that when MLSS levels in the reactor are elevated, the TN removal efficiencies is also higher, and the phenomenon of SND is more pronounced [20]. Additionally, introducing different organic substrates can enhance denitrification activity by promoting the growth of various genera of bacteria capable of reducing nitrate [34], which further improves nitrogen removal efficiency. When comparing DO_1 and DO_2 with the average DO concentration DO_3 in the anoxic zone of Mode A, we find that DO_3 has an average value of 0.4 mg L^{-1}, which is within the normal range for the anoxic zone. Additionally, considering the high TN removal efficiencies in Mode A (72% for Mode A compared to 65 and 62% for Mode B at recirculation ratios of 400 and 500%, respectively), this also demonstrates that increasing the system's sludge concentration can mitigate the effects of high recirculation ratios on the DO levels in the anoxic zone, thereby preserving the optimal working conditions.

In summary, increasing the internal recirculation ratio in the bioreactor (Mode A) can enhance the nitrogen removal efficiency of the system. To mitigate the impact of elevated DO levels in the anoxic zone resulting from the increased recirculation ratio, it is essential to implement oxygen removal measures for the return stream. Experimental results demonstrate that raising the system's sludge concentration can effectively prevent the adverse effects of high DO levels in the anoxic zone caused by high recirculation ratios.

3.4 DO recovery analysis

In the high recirculation ratio operation mode (Mode A), the initial DO concentration is monitored before each run, with the DO concentrations in the aerobic zone measured as shown in Table 4.

From the table above, we can see that the aeration pump not only allows for multiple recirculation of mixed liquor but also helps recover DO. Calculations indicate that the average DO recovery efficiency from the aeration pump during the monitoring period was 32%. To ensure the normal operation of the aerobic zone, it is essential to maintain a sufficient DO concentration. In aerated treatment plants, the energy required for aeration accounts for 60 to 65% of the total energy consumption

Table 4 Calculation table of DO recovery

Trial cycle (d) Concentration	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Aeration DO contribution (mg L^{-1})	1.7	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.7	1.7	1.7	1.7	1.8
DO recycling (mg L^{-1})	0.8	0.9	0.8	0.8	0.8	0.8	0.8	0.7	0.8	0.8	0.8	0.8	0.8	0.7
DO recovery (%)	33	34	31	32	30	32	32	31	30	31	32	33	31	29

of wastewater treatment facilities [35]. The combination of high concentration activated sludge systems with high internal recirculation allows for a reduction in the aeration supply in the aerobic zone, which in turn decreases aeration energy consumption and operational costs. This approach underscores the practical significance of energy conservation and cost reduction in this experiment.

3.5 DO Energy consumption analysis

3.5.1 Calculation of ventilation volume

Under both the high recirculation ratio (Mode A) and the conventional internal recirculation ratio (Mode B) operation modes, the DO concentration in the bioreactor is maintained at 2.5 mg L^{-1}. The airflow rate is monitored and recorded hourly, and the average airflow for each operational cycle is calculated. The monitoring data is presented in Table 5.

According to Table 5, the average daily ventilation of mode A and mode B was 3 and 2 m^3 h^{-1}, respectively, throughout the test cycle.

3.5.2 Energy consumption calculations

The standard coal consumption equivalent method is used in this energy consumption calculation, according to the"General Principles for Comprehensive Energy Consumption Calculation"GB/T2589-2008 Appendix A, and the reference coefficient of standard coal consumption for energy consumption discount is about 0.12.

(1) Large Proportional Reflow (Mode A)

According to Table 5, The average ventilation rate under the large-scale internal recirculation mode with the given energy consumption discount is 3.81 m^3 h^{-1}.

The operating parameters of the air compressor are 1.5 m^3 min^{-1}, 7.5 kW, P=0.6–1.0 MPa. The air compressor adopts intermittent operation.

Equation (1) calculates that the daily power consumption of the air compressor is 7.62 kWh. Therefore, the consumption of pared coal is:

$$7.62 \times 0.12 = 0.92(kgce) \tag{2}$$

(2) Conventional internal reflux (Mode B)

According to Table 5, The average ventilation of conventional internal reflux mode with the given energy consumption discount is 2.60 m^3 h^{-1}. Equation (1) calculates that the daily power consumption of the air compressor is 5.20 kWh.

Mode B uses one 95 W bottom suction pump as the internal return pump, and its daily power consumption is as follows:

$$P_3 = 0.095 \times 24 = 2.3(\text{kWh}) \tag{3}$$

Therefore, the consumption of pared coal is:

$$(5.2 + 2.3) \times 0.12 \approx 0.9(kgce) \tag{4}$$

Comparing the daily operating energy consumption of the two operating modes, the operating energy consumption of mode A and mode B are similar, respectively 0.92 and 0.90 kgce. Considering that the scale of the activated sludge reactor in this experiment is relatively small, the energy consumption of the mixed liquor recirculation pump is low. The primary energy consumption is

Table 5 Ventilation recording chart

Trial cycle (d) Ventilation (m^3 h^{-1})	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mode A	3.81	3.78	3.76	3.71	3.68	3.74	3.76	3.83	3.85	3.89	3.82	3.87	3.94	3.91
Mode B	2.48	2.62	2.47	2.54	2.57	2.46	2.71	2.74	2.67	2.63	2.58	2.61	2.66	2.59

still concentrated in the air compressor, which does not fully reflect the energy consumption and management advantages brought by a high proportion of recirculation systems. If the experimental setup is applied to the bioreactors of large-scale wastewater treatment plants, the approximately 30% DO recovery efficiency could lead to significant savings in operational energy consumption. Additionally, the convenience of replacing conventional mixed liquor recirculation pumps will enhance its overall advantages. The conclusions of this study not only enhanced the nitrogen removal efficiency from wastewater but also achieved the recovery and reuse of dissolved DO. In line with sustainable development goal 6: Clean Water and Sanitation, specifically target 6.3, which aims to"substantially increase the global recycling and safe reuse of waste,"this study contributes to the advancement of global sustainability objectives. However, when implemented on a large scale, potential environmental impacts must also be considered. If not managed properly, the high-concentration activated sludge used in this experiment could lead to sludge bulking, resulting in environmental pollution. Additionally, the reaction process may produce unpleasant odors, which could adversely affect the quality of life for nearby residents.

3.6 Development and prospects

When implementing the findings of this study, it is important to consider that the high MLSS system requires a large area. Additionally, it is necessary to incorporate an anoxic tank and address issues related to sludge treatment costs. If the findings of this experiment are applied to wastewater treatment in industries such as food and beverage, the high removal efficiencies of organic matter achieved in this study could prove to be highly beneficial. However, in the case of pharmaceutical wastewater, it may have detrimental effects on the microorganisms in activated sludge, leading to a reduction in removal efficiency. Furthermore, this paper focuses solely on the impact of high MLSS system and the effect of significant internal recycling ratios on pollutant removal in bioreactors. Future research should further investigate the enhanced nitrogen removal potential associated with higher recycling ratios and determine the optimal recycling ratio for achieving the best denitrification efficiency. In this study, air-lift pumps were used to enhance the recycling ratio. Future research could explore the integration of electrochemical processes to reduce energy consumption further and improve overall energy efficiency.

4 Conclusions

This study demonstrates that applying high MLSS system for high-rate internal recirculation leads to significantly higher nitrogen removal efficiencies compared to conventional internal recirculation. Additionally, it shows notable improvements in the removal of other pollutants and energy savings. However, excessive reflux ratios can increase the amount of DO carried by the nitrified effluent, and excessively high DO concentrations can disrupt the working environment of the anoxic zone, thereby inhibiting denitrification. Increasing the sludge concentration can rapidly consume DO, thereby enhancing the overall efficiency of wastewater treatment. Furthermore, this study demonstrates the potential to recover approximately 30% of DO, which can subsequently reduce the aeration supply in the aerobic zone, lower aeration energy consumption, and decrease operational costs. Overall analysis reveals that employing high-concentration activated sludge systems can save 1.8% in operational energy consumption, which holds significant practical implications for the retrofitting of wastewater treatment plants. However, this study represents only a small-scale exploratory experiment conducted in a laboratory setting on the application of high MLSS system for high-rate internal recirculation in bioreactors. In practical engineering applications, it is essential to pay attention to the selection and cultivation methods of activated sludge, as well as to control the return ratio and DO concentration effectively. To facilitate its early application in engineering practice, future efforts will focus on scaling up the experiments and conducting application trials in wastewater treatment plants. This will allow for further investigation into the energy-saving benefits associated with high MLSS system and their potential for achieving a high rate of internal recycling.

Acknowledgements

This study was supported by the funding and technical assistance from China Municipal Engineering Zhongnan Design and Research Institute. We thank them for their support throughout our research process. We also acknowledge Natural Science Foundation of Sichuan Province (No. 2022NSFSC0221) for partially supporting this study.

Authors' contributions

Conceptualization, B.L.; methodology, B.L. and Q.C.; software, Y.L.; validation, H.H. and B.L.; formal analysis, Y.L. and J.Y.; investigation, W.H.and X.Z.; resources, B.L. and Y.L.; data curation, Y.L. and Y.Y.; writing—original draft preparation, Y.L.; writing—review and editing, Y.L. and B.L.; visualization, Y.H. and Y.L.; supervision, B.L. and Y.L.; project administration, W.H. and Q.C.; funding acquisition, W.H. and Y.H. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by Research on the transformation of fixed circulating bed biofilm process technology, grant number 2022-YF05-00830-SN; Research on the application of advanced oxidation technology for advanced treatment of soy sauce and wine industrial wastewater, grant number 222357.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors on request.

Declarations

Competing interests
Authors Yiqiang Huang were employed by the SOUTHWEST MUNICIPAL ENGINEERING DESIGN & RESEARCH INSTITUTE OF CHINA. Authors Weiwei Huang were employed by the company China Municipal Engineering Zhongnan Design and Research Institute Co., Ltd. Author Qiang Chen was employed by the China Municipal Engineering North China Design Research Institute Co., Ltd. Author Xiang Zhou was employed by the Suyi Design Group Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author details
[1]School of Architecture and Civil Engineering, Xihua University, Chengdu 610039, China. [2]Southwest Municipal Engineering Design & Research Institute of China, Chengdu 610200, China. [3]China Municipal Engineering Zhongnan Design and Research Institute Co., Ltd., Wuhan 430010, China. [4]China Municipal Engineering North China Design Research Institute Co., Ltd., Chengdu 610074, China. [5]Suyi Design Group Co., Ltd., Nanjing 210012, China.

Received: 29 October 2024 Accepted: 30 June 2025
Published online: 14 July 2025

References

1. Xi H, Zhou X, Arslan M, Luo Z, Wei J, Wu Z, et al. Heterotrophic nitrification and aerobic denitrification process: Promising but a long way to go in the wastewater treatment. Sci Total Environ. 2022;805:150212.
2. Hreiz R, Latifi MA, Roche N. Optimal design and operation of activated sludge processes: State-of-the-art. Chem Eng J. 2015;281:900–20.
3. Chen Y, Li B, Ye L, Peng Y. The combined effects of COD/N ratio and nitrate recycling ratio on nitrogen and phosphorus removal in anaerobic/anoxic/aerobic (A2/O)-biological aerated filter (BAF) systems. Biochem Eng J. 2015;93:235–42.
4. Zheng T, Xiong R, Li W, Wu W, Ma Y, Li P, et al. An enhanced rural anoxic/oxic biological contact oxidation process with air-lift reflux technique to strengthen total nitrogen removal and reduce sludge generation. J Clean Prod. 2022;348:131371.
5. Quan ZX, Jin YS, Yin CR, Lee JJ, Lee ST. Hydrolyzed molasses as an external carbon source in biological nitrogen removal. Bioresource Technol. 2005;96:1690–5.
6. Feng XC, Bao X, Che L, Wu QL. Enhance biological nitrogen and phosphorus removal in wastewater treatment process by adding food waste fermentation liquid as external carbon source. Biochem Eng J. 2021;165:107811.
7. Yan X, Han Y, Li Q, Sun J, Su X. Impact of internal recycle ratio on nitrous oxide generation from anaerobic/anoxic/oxic biological nitrogen removal process. Biochem Eng J. 2016;106:11–8.
8. Li Y, Liu S, Lu L, Wang J, Huang G, Chen F, et al. Non-uniform dissolved oxygen distribution and high sludge concentration enhance simultaneous nitrification and denitrification in a novel air-lifting reactor for municipal wastewater treatment: A pilot-scale study. Bioresource Technol. 2023;384:129306.
9. Ni BJ, Pan Y, van den Akker B, Ye L, Yuan Z. Full-scale modeling explaining large spatial variations of nitrous oxide fluxes in a step-feed plug-flow wastewater treatment reactor. Environ Sci Technol. 2015;49:9176–84.
10. Wang Z, Liang H, Qu F, Ma J, Chen J, Li G. Start up of a gravity flow CANON-like MBR treating surface water under low temperature. Chem Eng J. 2013;217:466–74.
11. Luo B, Liu Y, Zhang Q, Yan Y, He H, Wang Y, et al. Study on influencing factors and chemical kinetics in the high-concentration simultaneous nitrification and denitrification (SND) process. Water. 2024;16:2334.
12. Yan X, Guo D, Qiu D, Zheng S, Jia M, Zhang M, et al. Effect of mixed liquor suspended solid concentration on nitrous oxide emission from an anoxic/oxic sequencing bioreactor. Desalin Water Treat. 2019;163:48–56.
13. Shi S, He X, He L, Fan X, Shu B, Zhou J, et al. Overlooked pathways of endogenous simultaneous nitrification and denitrification in anaerobic/aerobic/anoxic sequencing batch reactors with organic supplementation. Water Res. 2023;230:119493.
14. Jin P, Chen Y, Xu T, Cui Z, Zheng Z. Efficient nitrogen removal by simultaneous heterotrophic nitrifying-aerobic denitrifying bacterium in a purification tank bioreactor amended with two-stage dissolved oxygen control. Bioresource Technol. 2019;281:392–400.
15. Zhang Y, Yin Z, Liu M, Liu C. Enhancing simultaneous nitrification and denitrification in a plant-scale integrated fixed-film activated sludge system: Focusing on the cooperation between activated sludge and biofilm. Chem Eng J. 2024;496:154322.
16. Li X, Huang Y, Yuan Y, Bi Z, Liu X. Startup and operating characteristics of an external air-lift reflux partial nitritation-ANAMMOX integrative reactor. Bioresource Technol. 2017;238:657–65.
17. Meng Q, Yang F, Liu L, Meng F. Effects of COD/N ratio and DO concentration on simultaneous nitrifcation and denitrifcation in an airlift internal circulation membrane bioreactor. J Environ Sci China. 2008;20:933–9.
18. Li J, Li J, Wang B, Wang Z, Li X, Wang S, et al. Stable enhanced nitrogen removal from low COD/N municipal wastewater via partial nitrification-anammox in the traditional continuous anoxic/oxic process through bio-augmentation of partial nitrification sludge under decreasing temperatures. Bioresource Technol. 2022;363:127953.
19. Wu T, Ding J, Yang SS, Zhong L, Liu BF, Xie GJ, et al. A novel cross-flow honeycomb bionic carrier promotes simultaneous nitrification, denitrification and phosphorus removal in IFAS system: Performance, mechanism and keystone species. Water Res. 2022;225:119132.
20. Li D, Li W, Zhang D, Zhang K, Lv L, Zhang G. Performance and mechanism of modified biological nutrient removal process in treating low carbon-to-nitrogen ratio wastewater. Bioresource Technol. 2023;367:128254.
21. Zhao L, Zhang C, Bao M, Lu J. Advanced treatment for actual hydrolyzed polyacrylamide-containing wastewater in a biofilm/activated sludge membrane bioreactor system: Biodegradation and interception. Biochem Eng J. 2019;141:120–30.
22. Yang X, Xu Y, Naraginti S, Sathishkumar K, Wei X, Sun SP, et al. Catalytic enhancement of microbial denitrification by FeVO4@biochar: Insight into the extra cellular polymeric matrix mechanism. J Environ Chem Eng. 2024;12:113629.
23. Ren W, Cao F, Chai B, Jin P, Ju K. Enhancing nitrogen removal from domestic sewage with low C/N ratio using a biological aerated filter system with internal reflux-coupled intermittent aeration. Biochem Eng J. 2022;185:108532.
24. Cai Y, Li X, Zaidi AA, Shi Y, Zhang K, Feng R, et al. Effect of hydraulic retention time on pollutants removal from real ship sewage treatment via a pilot-scale air-lift multilevel circulation membrane bioreactor. Chemosphere. 2019;236:124338.
25. Purba LDA, Ibiyeye HT, Yuzir A, Mohamad SE, Iwamoto K, Zamyadi A, et al. Various applications of aerobic granular sludge: A review. Environ Technol Inno. 2020;20:101045.
26. James SN, Vijayanandan A. Recent advances in simultaneous nitrification and denitrification for nitrogen and micropollutant removal: a review. Biodegradation. 2023;34:103–23.
27. Wen J, LeChevallier MW, Tao W. Nitrification kinetics and microbial communities of activated sludge as a full-scale membrane bioreactor plant transitioned to low dissolved oxygen operation. J Clean Prod. 2020;252:119872.
28. Wu L, Zhang L, Shi X, Liu T, Peng Y, Zhang J. Analysis of the impact of reflux ratio on coupled partial nitrification–anammox for co-treatment of mature landfill leachate and domestic wastewater. Bioresource Technol. 2015;198:207–14.
29. Layer M, Villodres MG, Hernandez A, Reynaert E, Morgenroth E, Derlon N. Limited simultaneous nitrification-denitrification (SND) in aerobic granular sludge systems treating municipal wastewater: Mechanisms and practical implications. Water Res X. 2020;7:100048.
30. Zhu GC, Lu YZ, Xu LR. Effects of the carbon/nitrogen (C/N) ratio on a system coupling simultaneous nitrification and denitrification (SND) and denitrifying phosphorus removal (DPR). Environ Technol. 2021;42:3048–54.
31. Anjali G, Sabumon PC. Development of simultaneous partial nitrification, anammox and denitrification (SNAD) in a non-aerated SBR. Int Biodeter Biodegr. 2017;119:43–55.
32. Tian X, Li X, Dong P, Ren Z, Ji X, Bian D. The treatment effect and denitrification mechanism of low-temperature and low-carbon source municipal

wastewater treated by micro pressure swirl reactor. J Water Process Eng. 2022;49:103027.
33. Insel G, Hocaoglu SM, Cokgor EU, Orhon D. Modelling the effect of biomass induced oxygen transfer limitations on the nitrogen removal performance of membrane bioreactor. J Membrane Sci. 2011;368:54–63.
34. Rajta A, Bhatia R, Setia H, Pathania P. Role of heterotrophic aerobic denitrifying bacteria in nitrate removal from wastewater. J Appl Microbiol. 2020;128:1261–78.
35. Rosso D, Stenstrom MK. Surfactant effects on α-factors in aeration systems. Water Res. 2006;40:1397–404.

Publisher's Note