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Pilot Study on the Treatment of Rural Domestic Wastewater with Low C/N Ratio Using the AO-MABR Process

Shuili Yu [1, *], Yuesong Liu [2]

[1] State Key Laboratory of Pollution Control and Resources Reuse, College of Environmental Science and Engineering, Tongji University, Shanghai, 200092, PR China
[2] Tongji University, Shanghai, 200092, PR China

Abstract: To address the poor removal efficiencies of chemical oxygen demand (COD), ammonia nitrogen, and total nitrogen (TN) by existing treatment processes for rural domestic wastewater with low carbon-to-nitrogen (C/N) ratios, an integrated AO-MABR process was developed and evaluated in a field pilot-scale study. The results demonstrated that the optimal operational parameters of the process were as follows: hydraulic retention time (HRT) of 3.0 h, membrane aeration pressure of 20 kPa, and internal reflux ratio of 200%. Under these optimal conditions, when the influent C/N ratio ranged from 3 to 4, the average removal efficiencies of COD, ammonia nitrogen, and TN by the AO-MABR system reached 91.28%, 86.52%, and 86.67%, respectively, with corresponding effluent concentrations of 26.87 mg/L, 2.65 mg/L, and 4.98 mg/L. The integrated AO-MABR process exhibited superior pollutant removal performance compared with conventional treatment technologies.

Keywords: Membrane Aerated Biofilm Reactor, Low C/N Ratio, Domestic Wastewater, Chemical Oxygen Demand, Total Nitrogen.

1. Introduction

With the continuous development of wastewater treatment infrastructure in China, urban sewage treatment projects have advanced rapidly in recent years. However, in some counties and towns, the performance of sewage treatment is unsatisfactory due to inadequate management practices in wastewater treatment plants (WWTPs). At present, a limited number of rural WWTPs in China achieve qualified effluent standards [1], and some remote villages and towns even lack wastewater treatment facilities entirely. According to relevant statistical analyses, approximately 95% of rural domestic wastewater in China is discharged directly without treatment by WWTPs, resulting in severe pollution of more than 90% of water bodies. About 78% of rural river sections fail to meet the water quality criteria for drinking water sources, and more seriously, half of the groundwater in rural areas has been contaminated [2].

Rural water pollutant emissions account for 50% of the total national water pollutant discharge [3]. As of April 2023, the average treatment rate of rural domestic wastewater nationwide was approximately 31% [4]. The Ministry of Ecology and Environment has explicitly stipulated that the treatment rate of rural domestic wastewater in China should reach 40% by 2025 [5]. In view of the poor performance of rural wastewater treatment, especially the high rate of excessive total nitrogen (TN) in effluent, the low carbon-to-nitrogen (C/N) ratio of raw wastewater is recognized as one of the critical factors leading to TN non-compliance [6]. Generally, the C/N ratio (BOD_5/TN) of raw wastewater requiring TN removal should be no less than 4 [7].

Although the conventional anoxic-oxic (AO) process features a simple structure and flexible operation in wastewater treatment applications, it still presents several limitations. Owing to the lack of specific measures for denitrifying carbon source enrichment, nitrogen removal efficiency is susceptible to fluctuations in influent C/N ratio and temperature, resulting in low carbon source utilization. Insufficient carbon sources during the denitrification phase lead to incomplete organic matter removal. The AO process is sensitive to dissolved oxygen, hydraulic retention time and water quality variations, imposing relatively high requirements for operation and management. Overall, its performance in simultaneous nitrogen and phosphorus removal and operational stability needs to be further improved.

Membrane-aerated biofilm reactor (MABR) is an innovative reactor that integrates membrane technology and biotechnology [8]. It delivers oxygen directionally within membrane fibers to form a dissolved oxygen gradient, facilitating the stratified enrichment of aerobic and anaerobic microbial communities. The synergistic metabolism of diverse microorganisms within the biofilm enables simultaneous nitrification and denitrification (SND) [9–12], thereby achieving deep and synchronous nitrogen removal. This technology reduces aeration energy consumption by 30%–50% [13], aligning with the requirements of low-carbon development.

In this study, a pilot-scale experiment was conducted based on a rural WWTP in Zhejiang Province, targeting rural domestic wastewater with a low C/N ratio. An integrated AO-MABR process was established by coupling membrane-aerated biofilm reactor with the conventional anoxic-oxic (AO) process to enhance wastewater treatment performance. The optimal operational conditions of the reactor were investigated. On this basis, the reactor was operated continuously to evaluate the removal efficiencies of chemical oxygen demand (COD), ammonia nitrogen and total nitrogen from actual rural domestic wastewater under the optimized parameters. Combined with the analysis of microbial community structure, this study aims to provide a technical reference for the field of rural domestic wastewater treatment.

2. Materials and Methods

2.1. Composition of the AO-MABR Process

Raw water flows from the regulating tank successively through the anaerobic tank, MABR membrane tank, aerobic tank, sedimentation tank, filtration tank and clean-water tank, and is then discharged after disinfection. Blowers are employed to supply oxygen to the aerobic tank and the MABR tank. Aeration rates are adjusted by valves, and dissolved oxygen concentrations are monitored using a dissolved oxygen meter to maintain the desired levels in the reaction tanks. Sludge generated from the wastewater treatment system is discharged into a sludge storage tank for temporary retention and periodically transferred to the sludge treatment system of the wastewater treatment plant.

2.2. Experimental Setup

The experimental apparatus was equipped with a programmable logic controller (PLC) to realize automatic control throughout the operation process based on preset procedures for flow rate, liquid level and other parameters. A relay control system and a manual control device were also configured as auxiliary systems. The operation mode could be adjusted according to the real-time influent quality, influent quantity and effluent quality on site to meet operational requirements.

The apparatus box was made of stainless steel. The main reactor consisted of an anoxic tank, a membrane tank, an aerobic tank, a sedimentation tank, a filter tank and a disinfection tank. The membrane module unit was installed in the membrane tank.

An air compressor supplied oxygen to the membrane module unit through aeration pipes at the bottom of the anoxic tank and to the microporous diffusers at the bottom of the aerobic tank. A gas flow meter and a pressure gauge were installed on the air inlet pipeline. A submersible sewage pump was adopted for influent feeding, and the disinfected supernatant was sampled to determine the effluent quality. (3) The color is more gorgeous

In the development of traditional embroidery, many patterns have very gorgeous colors. This gorgeous color is extremely recognizable, which makes the whole embroidery artistry by going up one flight of stairs. At the same time, in the process of creating embroidery works, people should also show local famous folk paintings through color matching. Common TINT, there are red with green, red with black and red with yellow. Very traditional color matching has a strong connection with the cultural characteristics of our country. Moreover, some folk embroidery patterns will also use different treatment methods such as retrograde halo and color halo to adjust the color pertinently, so that the artistic appeal of embroidery can be further improved

2.2.1. Anoxic Tank

The total effective volume of the anoxic tank and the membrane tank was 4.7 m3. Aeration pipes and a sludge return pipe were arranged inside the tank. Meanwhile, a reserved dosing pipe was installed on the pipeline connecting to the membrane tank.

2.2.2. Membrane and Membrane Module

The hollow fiber membrane module used in the experiment was made of PVDF material, with a single membrane filament diameter of 0.9 mm. The pH tolerance range and maximum operating temperature of the membrane filaments were 2–13 and 69∘C, respectively.

The membrane module enabled stable oxygen transfer to microorganisms attached to the membrane filaments without bubble formation. Air entered from one end of the membrane filaments and permeated gradually outward through the hollow fiber structure, and the oxygen released was subsequently consumed by the biofilm attached to the membrane surface. The membrane module is shown in Figure 1.

Figure 1. Membrane module

2.2.3. Aerobic Tank

The effective volume of the aerobic tank was 1.92 m3, with aeration pipes installed inside. A reserved dosing pipe was also arranged on the pipeline connecting to the sedimentation tank.

2.2.4. Sedimentation Tank

The effective volume of the sedimentation tank was 1.6 m3. Settled sludge was pumped back to the anoxic tank and membrane tank by an air pump.

2.2.5. Filter Tank

The effective volume of the filter tank was 1.04 m3, employing multi-stage granular filter media for filtration. Backwashing pipelines and an overflow outlet were equipped, and simultaneous air-water backwashing was adopted.

2.2.6. Disinfection Tank

The effective volume of the disinfection tank was 0.8 m3, and ultraviolet (UV) disinfection was applied.

2.3. Experimental Influent

The experiment was conducted at a wastewater treatment plant in Zhejiang Province, using the raw influent of the plant as the treatment object. Main water quality indicators of the raw wastewater were monitored once per day during the experiment.

(1) During biofilm formation, synthetic wastewater was prepared at a C/N ratio of 6, with COD maintained at approximately 300 mg/L and total nitrogen at about 50 mg/L. Sodium acetate and anhydrous ammonium chloride were used as carbon and nitrogen sources, respectively. The daily dosage was adjusted according to actual conditions.

(2) the actual wastewater was taken from the wastewater treatment plant, representing typical rural domestic wastewater. The system temperature ranged from 28.3 ℃ to 29.8 ℃, influent pH was 7.13–8.31, influent COD was 87.68–288.65 mg/L, ammonia nitrogen was 35.44–59.30 mg/L, and total nitrogen was 50.12–74.55 mg/L.

2.4. Analytical Methods

Table 1. Detection Methods and Standards for Conventional Water Quality Indicators

No.	Item	Instrument Brand and Model	Detection Method
1	COD	Hach DRB200, DR6000	Rapid digestion spectrophotometry
2	TN	Shanghai Lengguang 756S UV Spectrophotometer	Alkaline potassium persulfate UV spectrophotometry
3	NH_4^+-N	Shanghai Lengguang 756S UV Spectrophotometer	Nessler's reagent spectrophotometry
4	NO_3^--N	Shanghai Lengguang 756S UV Spectrophotometer	Ultraviolet spectrophotometry
5	pH	Mettler Toledo pH Meter F2-field	Direct measurement method
6	DO	HACH HQ40d	Luminescent dissolved oxygen (LDO) fluorometric method

The conventional water quality analysis methods in this study were mainly referenced from the 4th edition of Monitoring and Analytical Methods for Water and Wastewater and Standard Methods for the Examination of Water and Wastewater.

COD, total nitrogen (TN), nitrate nitrogen (NO_3^--N), ammonia nitrogen (NH_4^+-N) and other indicators were determined using water quality analyzers in accordance with relevant standards.

Dissolved oxygen (DO) was measured with a probe-type instrument, while pH and temperature were determined using portable meters.

The main analytical instruments and corresponding detection methods used in the experiment are listed in Table 1.

3. Results and Discussion

3.1. Biofilm Formation

Biofilm formation was carried out by inoculating sludge from the anoxic and aerobic tanks of the wastewater treatment plant. When the aeration pressure of the membrane module was set at 10 kPa, the dissolved oxygen (DO) concentration in the anoxic tank was controlled at approximately 0.2 mg/L. Accordingly, the membrane aeration pressure was maintained at 10 kPa, and the aeration rate of the microporous diffusers at the bottom of the aerobic tank was adjusted to keep the DO concentration in the aerobic tank at around 2 mg/L. After 7 days of static aeration, a pale yellow biofilm appeared on the membrane surface. Successful biofilm formation was indicated when the color gradually deepened from pale yellow to tan and the biofilm thickness increased significantly.

The biofilm formation experiment was conducted based on a pre-existing AO setup, with the MABR module installed in the membrane tank. At this stage, the mixed liquor suspended solids (MLSS) in the anoxic tank was approximately 2600 mg/L, suggesting an abundant population of functional microorganisms. Abundant Vorticella and Rotifera were observed under microscopy, indicating that the sludge was sufficiently mature and suitable for biofilm colonization.

The aeration pressure of the membrane was adjusted below its bubble point pressure via valves to avoid bubble formation. During MABR biofilm formation, continuous influent feeding was maintained for 48 hours. The DO in the anoxic tank was controlled below 0.20 mg/L, while that in the aerobic tank was maintained at approximately 2.00 mg/L. The influent flow rate was 1.0 m^3/h, with a hydraulic retention time (HRT) of 1.0 h in the anoxic tank and 2.0 h in the aerobic tank. Wastewater was fed by a submersible sewage pump, and the mixed liquor recirculation ratio was set at 200%. The influent concentrations of COD, ammonia nitrogen, and total nitrogen were controlled at approximately 300 mg/L, 40 mg/L, and 50 mg/L, respectively, ensuring a stable COD/TN ratio of around 6. During the experiment, effluent samples were collected and analyzed at regular intervals, and the adhesion status of the biofilm on the membrane module was observed simultaneously.

As shown in Figure 2(a), a small amount of activated sludge began to attach to the surface of the hollow-fiber membrane filaments on the first day of biofilm formation, but the biomass was insufficient to support substantial microbial growth and metabolism. By the 14th day (Figure 2(b)), most membrane filaments were covered with a thin, brownish biofilm, with noticeably increased biomass and gradually thickening structure. On the 27th day (Figure 2(c)), microorganisms secreted abundant extracellular polymeric substances (EPS), which formed a visible mucous layer on the biofilm surface and facilitated stable adhesion of more microbes to the hollow-fiber membranes. No significant further increase in biofilm thickness or biomass was observed by visual inspection, indicating that the biofilm on the membrane surface had reached a stable and mature state.

(a) Day 1 (b) Day 14 (c) Day 27

Figure 2. Surface morphology of the membrane module before and after biofilm formation

As shown in Figure 3(a), on the 15th day of biofilm formation, samples of biofilm attached to the surface of the hollow-fiber membrane filaments were collected using a scalpel and observed under an optical microscope. Relatively dense zoogloea had formed in the biofilm, accompanied by a number of highly active microorganisms, indicating that the microorganisms in the biofilm were growing and reproducing rapidly in a normal and healthy manner.

Sampling and microscopic examination were performed again on the 28th day of biofilm formation. As shown in Figure 3(b), the zoogloea had become compact and dense, with both dark brown mature zoogloea and lighter-colored newly formed zoogloeal coexisting. Meanwhile, microorganisms with excellent activity were still observed.

(a) Day 15 (b) Day 28

Figure 3. Microscopic examination of biofilm at different stages (Magnification: 10×40)

3.2. Optimization of Operational Parameters

The carbon and nitrogen removal performance of the system was enhanced by adjusting operational conditions. An excessively short hydraulic retention time (HRT) prevents sufficient reaction between wastewater and microorganisms, resulting in unsatisfactory treatment efficiency, whereas an overly long HRT leads to excessive treatment capacity and unnecessary resource waste. A proper mixed liquor recirculation ratio (internal recirculation ratio) can improve the nitrogen removal capacity of the reactor. The HRT and internal recirculation ratio were adjusted by regulating the influent submersible sewage pump and internal airlift reflux pump to optimize the system operational parameters.

3.2.1. Effect of HRT on Treatment Performance of the System for Low C/N Wastewater

The water temperature ranged from 29.9 °C to 30.8 °C, and the influent pH was 6.88–7.21. The influent flow rate was maintained at 1.0 m³/h. The dissolved oxygen (DO) in the anoxic tank was controlled at 0.20 mg/L with mixed liquor suspended solids (MLSS) of 2303–3200 mg/L, while DO in the aerobic tank was controlled at 2.00 mg/L with MLSS of 1539–2366 mg/L. The effluent quality variations of the coupled process were investigated at HRT values of 1.0 h, 1.5 h, 2.0 h, 2.5 h, 3.0 h, and 3.5 h, respectively. The water quality variations and pollutant removal performance of the coupled process are shown in the figures.

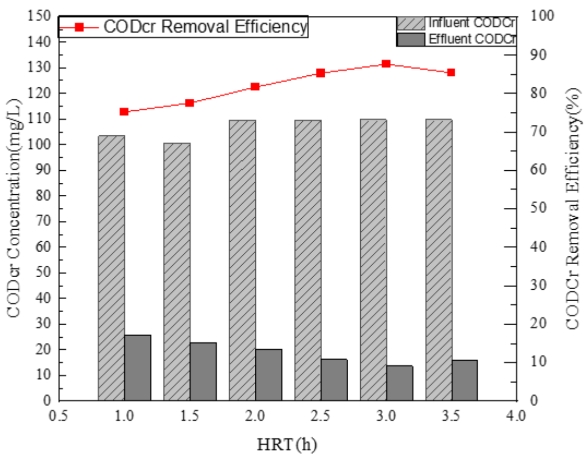

Figure 4. Treatment Effect of COD at Different HRTs

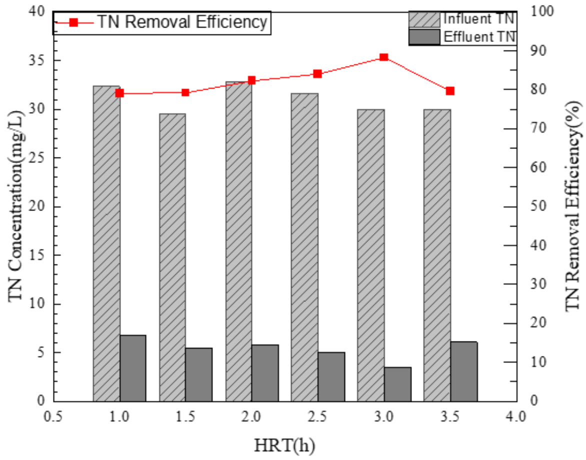

Figure 5. Treatment Effect of TN at Different HRTs

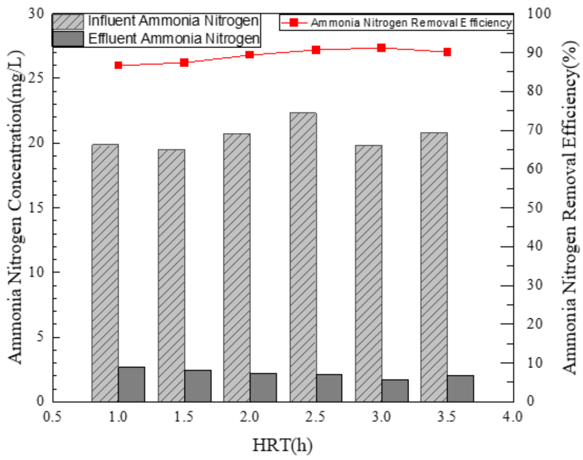

Figure 6. Treatment Effect of Ammonia Nitrogen at Different HRTs

As shown in the Figure 4, with the gradual change of HRT, the average COD removal efficiency of the AO-MABR coupled reactor increased successively to 75.19%, 77.52%, 81.65%, 85.29%, and 87.61%. Effluent COD decreased gradually with increasing HRT, indicating that a longer HRT improved COD removal performance per unit time.

As shown in the Figure 5, with increasing HRT, the total nitrogen removal efficiency of the AO-MABR coupled reactor increased gradually to 79.10%, 79.25%, 82.25%, 84.04%, and 88.27%. The average total nitrogen removal load reached the maximum at an HRT of 3.0 h. This suggests that prolonging HRT increased the contact time between pollutants and microorganisms, thereby enhancing the ammonia nitrogen and total nitrogen removal capacity of the coupled system. The average ammonia nitrogen removal load also peaked simultaneously at an HRT of 3.0 h.

3.2.2. Effect of Internal Recirculation Ratio on Treatment Performance of the System for Low C/N Wastewater

The water temperature ranged from 30.3 °C to 32.5 °C, and the influent pH was 7.00–7.31. The influent flow rate was maintained at 1.0 m³/h. The dissolved oxygen (DO) in the anoxic tank was controlled at 0.20 mg/L with MLSS of 2310–3073 mg/L, while DO in the aerobic tank was controlled at 2.0 mg/L with MLSS of 1523–2409 mg/L. The effluent quality variations of the coupled process were investigated at internal recirculation ratios of 100%, 150%, 200%, 250%, 300%, and 350%, respectively. The water quality variations and pollutant removal performance of the coupled process are shown in the figures.

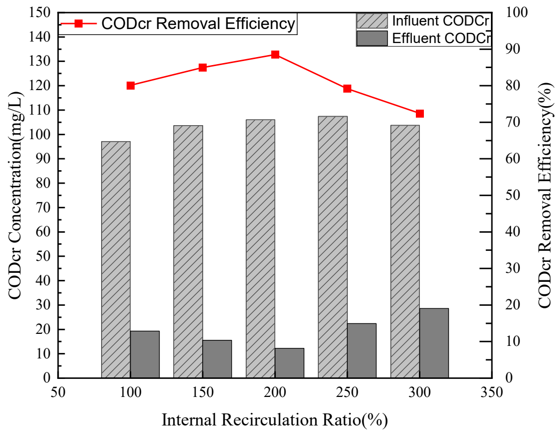

Figure 7. Treatment Effect of COD at Different Internal Recirculation Ratio

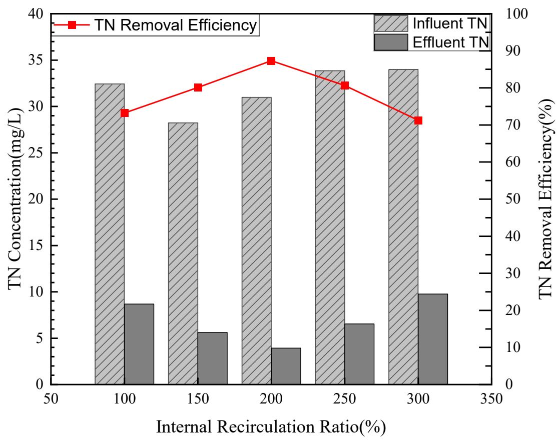

Figure 8. Treatment Effect of TN at Different Internal Recirculation Ratio

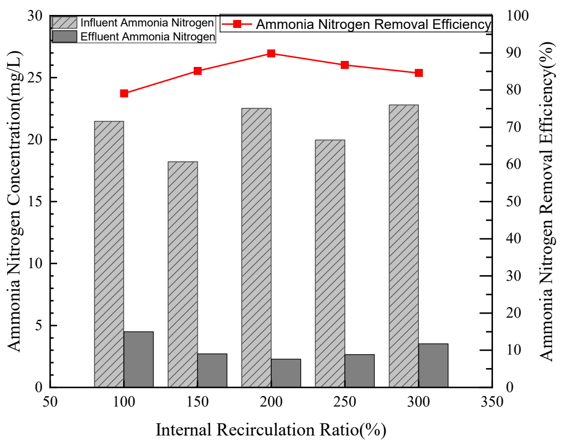

Figure 9. Treatment Effect of Ammonia Nitrogen at Different Internal Recirculation Ratio

As shown in the Figure 7, with the continuous increase of the internal recirculation ratio, the average COD removal efficiency of the AO-MABR coupled reactor first increased and then decreased, reaching 80.11%, 84.97%, 88.49%, 79.15% and 72.43% respectively. The reason was that an excessive internal recirculation ratio would lead to changes in the dissolved oxygen concentration in the anoxic tank and the membrane tank, thereby reducing the organic matter removal rate of the system. The effluent COD gradually decreased with the increase of the internal recirculation ratio. The increase of the internal recirculation ratio would enhance the COD removal effect per unit time.

As shown in Figure 8, with the increase of the internal recirculation ratio, the total nitrogen removal rate of the AO-MABR coupled reactor also first increased and then decreased, reaching 73.25%, 80.10%, 87.35%, 80.66% and 71.29% respectively. With the gradual increase of the internal recirculation ratio, the total nitrogen removal capacity of the device became stronger and stronger. The reflux of the nitrification solution brought a large amount of nitrate nitrogen to the anoxic tank and the membrane tank, improving the total nitrogen removal capacity of the device. When the internal recirculation ratio was greater than 200%, the total nitrogen removal rate of the device decreased. The analysis was that an excessive internal recirculation ratio would lead to unstable dissolved oxygen in the water of the anoxic tank and the membrane tank, so that denitrifying bacteria could not reproduce in the optimal growth space, thus inhibiting the denitrification reaction and reducing the total nitrogen removal rate of the device. Only an appropriate internal recirculation ratio could achieve better nitrogen removal and better synchronize the nitrification reaction and denitrification reaction.

As shown in Figure 9, when the internal recirculation ratio reached 100%, 150% and 200% respectively, the ammonia nitrogen removal rates of the AO-MABR coupled system were 79.06%, 85.12% and 89.84% respectively. When the internal recirculation ratio reached 250% and 300%, the ammonia nitrogen removal rate of the AO-MABR coupled system gradually decreased, but always remained around 85% at a relatively high level, and the overall ammonia nitrogen removal effect of the system was relatively stable.

3.2.3. Effect of Different Membrane Aeration Pressures on the Treatment Performance of the System for Low C/N Wastewater

The water temperature ranged from 29.9℃ to 30.8℃. The influent flow rate was maintained at 1.0m³/h. The dissolved oxygen in the anoxic tank was controlled at 0.20mg/L with MLSS ranging from 2218mg/L to 3195mg/L, and the dissolved oxygen in the aerobic tank was controlled at 2.0mg/L with MLSS ranging from 1628mg/L to 2381mg/L. The effluent quality variations of the coupled process were investigated when the hydraulic retention time of the MABR tank was 1.0h, 1.5h, 2.0h, 2.5h, 3.0h and 3.5h, respectively. The water quality variations and the pollutant removal effect of the coupled process are shown in the figures.

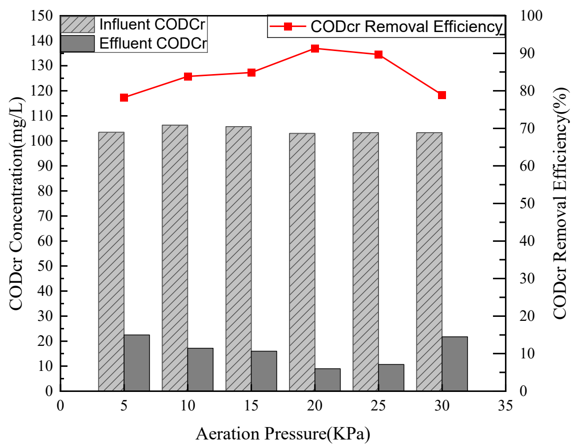

Figure 10. Treatment Effect of COD at Different Aeration Pressures

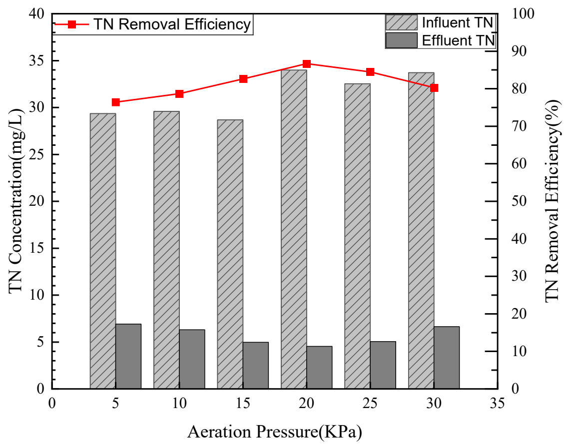

Figure 11. Treatment Effect of TN at Different Aeration Pressures

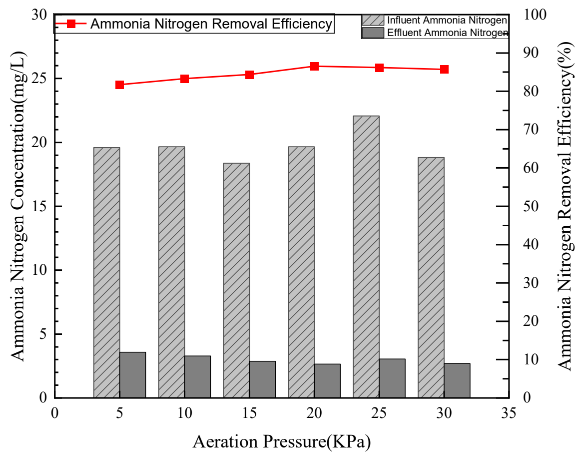

Figure 12. Treatment Effect of Ammonia Nitrogen at Different Aeration Pressures

As shown in the Figure 10, with the continuous increase of aeration pressure, the average COD removal efficiency of the AO-MABR coupled reactor increased overall, reaching 78.25%, 83.84%, 84.86%, 91.28%, 89.69% and 78.93% respectively. The effluent COD gradually decreased with the increase of aeration pressure. The increase of aeration pressure enhanced the COD removal effect per unit time. Excessively high membrane aeration pressure would inhibit the anaerobic and facultative anaerobic bacteria in the biofilm, and also cause the biofilm attached to the surface of fiber membrane filaments to loosen and fall off, which would reduce the COD removal efficiency of the AO-MABR coupled system.

As shown in Figure 11, with the increase of aeration pressure, the total nitrogen removal efficiency of the AO-MABR coupled reactor increased first and then decreased, reaching 76.42%, 78.70%, 82.64%, 86.67%, 84.48% and 80.31% respectively. The reason was that the MABR biofilm sloughed off due to excessive aeration intensity, and the dissolved oxygen concentration in the membrane tank increased accordingly. Although the activity of aerobic nitrifying bacteria was improved and the nitrification reaction proceeded more thoroughly, the higher dissolved oxygen concentration inhibited the activity of denitrifying bacteria, resulting in the failure of denitrification to proceed smoothly and the decline of total nitrogen removal capacity. In addition, most of the residual total nitrogen was in the form of NO3--N, which also reduced the simultaneous nitrification and denitrification capacity of the MABR biofilm.

As shown in Figure 12, when the aeration pressures were 5 KPa, 10 KPa, 15 KPa and 20 KPa respectively, the effluent ammonia nitrogen concentrations were 3.58 mg/L, 3.28 mg/L, 2.87 mg/L and 2.65 mg/L. Changing the aeration pressure had little effect on its treatment capacity. Ammonia nitrogen removal mainly depended on nitrifying bacteria, which are aerobic microorganisms and generally attached to the innermost layer of the MABR biofilm. If the aeration pressure was too low, the growth and development of aerobic nitrifying bacteria would be inhibited, leading to insufficient nitrification reaction and failure to achieve the expected effect.

3.3. Continuous Operation under Optimal Operating Conditions

Based on the experimental results of the effects of aeration pressure, hydraulic retention time and internal recirculation ratio on the performance of the coupled process, the optimal operating parameters of the device were determined as follows: membrane aeration pressure of 20 kPa, HRT of 3.0 h, and internal recirculation ratio of 200%. A one-month continuous experiment was conducted under these optimal parameters to investigate the operational performance of the reactor.

As shown in Figure 13, under the optimal parameters, the influent COD fluctuated between 70 mg/L and 220 mg/L, while the effluent COD was basically stable at 10 mg/L to 30 mg/L, which could meet the requirement of less than 40 mg/L specified in the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002) Level I A. The average COD removal efficiency was 87.57%, indicating excellent COD removal performance.

As shown in Figure 14, the influent ammonia nitrogen fluctuated between 14 mg/L and 28 mg/L under the optimal parameters, and the effluent ammonia nitrogen concentration was very low, stably maintained at 1 mg/L to 2 mg/L, with an average ammonia nitrogen removal efficiency of 92.36%. This demonstrated that sufficient oxygen supply in the reactor under the optimal conditions was favorable for the growth of ammonia-oxidizing bacteria, resulting in satisfactory ammonia nitrogen removal and a relatively thorough ammonia oxidation stage of nitrification.

As shown in Figure 15, the influent total nitrogen fluctuated between 25 mg/L and 40 mg/L under the optimal parameters, and the effluent total nitrogen was basically around 5 mg/L to 8 mg/L, which could satisfy the requirement of less than 8 mg/L specified in the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002) Level I A. The average total nitrogen removal efficiency was 81.24%, suggesting that the denitrification process proceeded to a certain extent and favorable total nitrogen removal was achieved under the optimal parameters.

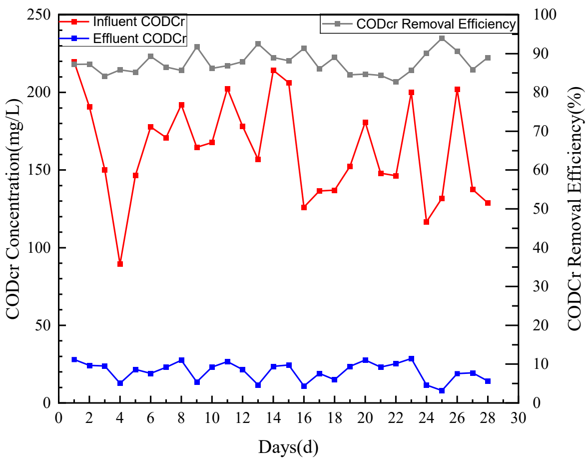

Figure 13. COD Removal Performance

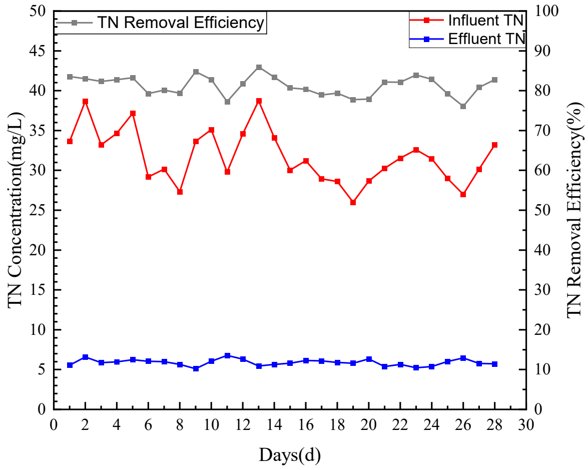

Figure 14. TN Removal Performance

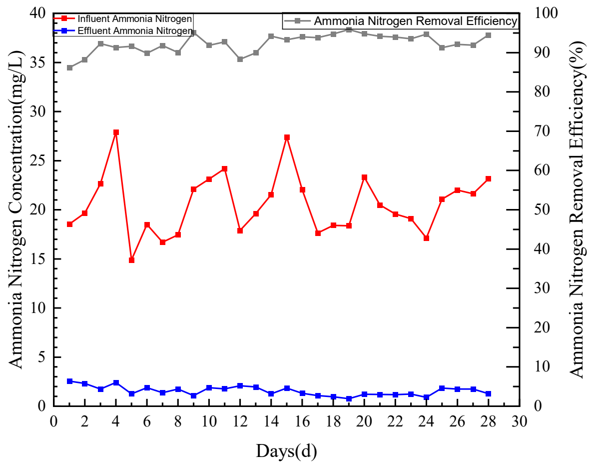

Figure 15. Ammonia Nitrogen Removal Performance

4. Conclusions

(1) In the operational parameter optimization of the AO-MABR coupled process for low C/N wastewater treatment, hydraulic retention time (HRT), internal recirculation ratio, and membrane aeration pressure exerted significant effects on the removal efficiencies of COD, ammonia nitrogen, and total nitrogen. Prolonging HRT gradually enhanced the pollutant removal capacity, with the optimal performance achieved at an HRT of 3.0 h. There existed an optimal internal recirculation ratio for nitrogen removal, and the total nitrogen removal efficiency peaked at 200%; either insufficient or excessive recirculation was unfavorable. Elevated membrane aeration pressure intensified nitrification, yet excessive pressure disrupted the biofilm structure and inhibited denitrification. The optimal membrane aeration pressure in this study was determined to be 20 kPa.

(2) Under the optimal operational conditions (membrane aeration pressure of 20 kPa, HRT of 3.0 h, internal recirculation ratio of 200%), the system exhibited excellent stability and treatment performance during one month of continuous operation. When the influent COD ranged from 70 to 220 mg/L, the effluent COD was stably controlled at 10–30 mg/L with an average removal efficiency of 87.57%, meeting the Level I A discharge standard specified in GB 18918-2002.

(3) The system achieved outstanding ammonia nitrogen removal. With the influent ammonia nitrogen varying between 14 and 28 mg/L, the effluent concentration was stably maintained at 1–2 mg/L, corresponding to a high average removal efficiency of 92.36%. This indicated sufficient oxygen transfer and high activity of nitrifying bacteria within the reactor, ensuring a thorough ammonia oxidation process.

(4) Favorable total nitrogen removal was also obtained. The influent total nitrogen was 25–40 mg/L, while the effluent was controlled at 5–8 mg/L with an average removal efficiency of 81.24%, satisfying the Level I A standard. This demonstrated that efficient simultaneous nitrification and denitrification occurred under the optimal parameters, enabling smooth denitrification and making the process suitable for advanced nitrogen removal from low C/N wastewater.

(5) The experimental results reveal that the AO-MABR coupled process possesses promising application potential for treating low C/N domestic sewage or slightly polluted water. Through rational regulation of operational parameters, stable and efficient carbon and nitrogen removal can be realized, providing a technical basis and reference for practical engineering applications.

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