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Membrane Contamination Control in the Intermittent Aeration Mode of Operation of the C-MBR Process for Campus Wastewater Reuse

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Abstract: Filtration backwashing is necessary for the effective operation of membrane modules, and intermittent aeration helps to remove nutrients, which can save energy and effectively control the occurrence of membrane contamination. In this study, membrane contamination was controlled using an MBR in intermittent aeration operation mode and a filtration backwash cycle; difficult organic matter and nitrogen (COD and NH_4^+-N) were used as the main contamination indicators for this study; and the main membrane contamination components, extracellular polymers (EPs), and soluble microbial products (SMPs) were detected. The results show that the average removal of COD and NH_4^+-N could reach 86.45% and 92.47%, respectively, with a 2.0 day intermittent aeration time and 9/1 min filtration backwash cycle mode, and it also helped to reduce the membrane contamination, as shown by a decrease of 11.87% in bound EPs (EPS_{Bound}) and an increase of only 5.32% in SMPs. Microbiological analyses revealed that Proteobacteria and Acinetobacter, as dominant bacteria (50.90%), were the main causes of membrane contamination.

Keywords: intermittent aeration; filtration backwashing; water reuse; membrane contamination control

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1. Introduction

Freshwater resources are diminishing globally, and water reuse is an effective way to address water scarcity. Water reuse can reduce the generation of wastewater and the demand for freshwater resources, as well as improve the ecological environment by reducing energy consumption and its environmental impacts such as water and land pollution [1]. Domestic sewage, snow, rainwater, and industrial wastewater treated in wastewater treatment plants can be used as sources of reclaimed water [2,3]. Schoolyard domestic sewage includes dormitory laundry, shower wastewater, canteen wastewater, and toilet flushing wastewater. Bath, laundry, and kitchen wastewater is called grey water (GW) [4]. Schoolyard domestic sewage has a high flow rate and contains a variety of organic substances and microorganisms, including fats, proteins, and carbohydrates [5]. These organic substances decompose easily and produce bad odors, and they also lead to the eutrophication of water bodies, triggering excessive algal blooms and increased oxygen consumption, affecting the surrounding ecological environment. While toilet wastewater is known as black water (BW) [6], the treatment of campus wastewater for water reuse requires centralized treatment methods for both GW and BW. Chemical, physical, biological, and electrochemical treatment processes can all be applied to the water reuse process [7–10]. Physical methods usually require pre-treatment to remove high concentrations of dissolved compounds; chemical methods are mainly used for suspended solids, organic matter, and surfactants but are not effective at removing nitrogen; electrochemical treatments are bactericidal, disinfectant, and deodorizing but have high energy consumption levels and high operating costs; and biological methods are highly suitable and cost-effective for this type of biochemically sound wastewater [11]. A water reuse process based on membrane filtration technology and biological treatment (i.e., using a membrane bioreactor (MBR)) can fully retain microorganisms and bring out the maximum advantages of the biological treatment process. MBR-treated water can be used for plant greening and landscape irrigation on campus, as well as to meet some non-potable water needs in building construction, such as building construction, road washing, and other uses. When reusing campus domestic wastewater, it is necessary to determine appropriate follow-up treatment measures as well as appropriate safety protection measures based on the quality of the water, the demand for its use, and the relevant regulations and standards to ensure the quality and safety of the reused water [12]. Fan et al. [6] explored the actual performance of a full-size air-ascending external recirculation membrane bioreactor (AEC-MBR) for treating toilet wastewater, and the effluent quality was better than the Chinese national reuse standard. Ren et al. [7] used an MBR and bioreactor aerated filters (BAFs) to treat GW, and the treated effluents reached the standard for the reuse of toilet flushing water; with the MBR's treatment, COD (chemical oxygen demand), ammonia nitrogen (NH_4^+-N), and turbidity were reduced by 60–90%, 80–90%, and 95–99%, respectively, which were better than the treatment effect of the BAF system. The MBR process has been successfully implemented in many cases in schoolyard domestic sewage and has shown the significant advantages of good treatment performance, a small footprint, and a low sludge-generation rate. The MBR process is simple to operate and has good system stability which can adapt to the fluctuation in and complexity of campus domestic wastewater. The effluent quality of the MBR process is stable and reliable, which can meet the requirements of campus domestic water and at the same time provides the possibility of secondary utilization, such as irrigation and landscape water.

However, energy consumption and membrane contamination still hinder the widespread application of the MBR process. Several aeration strategies have contributed to some extent to energy saving in wastewater treatment [13–15]. The implementation of the intermittent aeration (IA) method solves the problem of energy consumption and is a cost-effective solution. IA achieves the alternation of aerobic and anoxic phases in the same reactor, which reduces the supply of air in the reactor, resulting in a reduction in the nitrate content in the mixture returned from the nitrification-to-denitrification process and reducing the energy consumption generated by the nitrate reduction process [16]. Hasar et al. [17] showed that IA also has an excellent nutrient removal capability, with COD removal rates ranging from 88.3% to 99.3%. In addition to the problem of energy consumption, solving the issue of membrane contamination has been a hot topic discussed by researchers. It is necessary to develop and apply more advanced membrane contamination control strategies, such as online cleaning technology and chemical cleaning agents, in order to reduce the degree of membrane contamination, prolong the service life of the membrane, and maintain high flux and stable treatment performance in the process of realizing water reuse. Although the aeration of the blower has a certain flushing effect on membrane surface contamination, physical cleaning is far from the cleaning intensity of chemical cleaning. The use of the backwashing strategy to control membrane contamination is an effective means, while the use of cleaning agents with high cleaning intensities can improve the efficiency of chemical cleaning by 25% [1].

Considering the above factors, the main objective of this study is to gain an in-depth understanding of an MBR water reuse process which adopts an intermittent aeration mode, with the membrane modules being placed in separate reaction tanks to control the duration of the blast aeration. With COD and NH_4^+-N as the main water pollution indicators studied, the effects of the intermittent aeration mode and the filtration backwash cycle on the MBR process were analyzed, and the operating parameters of the process were optimized to grasp the biological performance of the system, including pollutant removal, the production of extracellular polymers (EPs) and soluble microbial products (SMPs), and the structure of microbial communities, which is important for the promotion of water reuse in the C-MBR process, which is of great significance in promoting the popularization and application of the C-MBR process.

2. Materials and Methods

2.1. Experimental Set Up

According to Figure 1, the experimental device adopts the MBR (C-MBR) water reuse process based on ceramic flat membranes for the campus wastewater of Guilin University of Technology, which combines biochemical treatment with membrane separation technology to directly treat campus domestic wastewater to meet the requirements of water reuse, and at the same time effectively reduces the cost of the maintenance and replacement of membranes [18]. The main body of the C-MBR process consists of anaerobic, aerobic, and membrane modules, of which the membrane module and aerobic biochemical tank are integrated. The effective volume of the C-MBR process was 150 m^3, and the volume ratio of the pre-reaction area (partially anaerobic area) to the main reaction area (aerobic area) was 2:3. The pre-reaction area was equipped with a mixer, and there was an aeration pipe laid under the main reaction area, with a submersible pump located in the regulating tank to complete the intake of water and a circulating pump located in the main reaction area to complete the circulation of the mixed liquid. A self-priming pump draws water from the membrane module. The membrane module used by the Japanese Meidensha Group provides a membrane pore size of 0.1 µm. It is an Al_2O_3 ceramic flat membrane, with a filtration mode for the external inlet and internal suction, having membrane dimensions of width × height × thickness of 280 mm × 1046 mm × 12 mm, respectively. The effective membrane area was 0.5 m^2. During the entire automated operation process, the PLC (Programmable Logic Controller) was set up by the electrical cabinet of the program to control the filtration pumps, circulating pumps, feed pumps, and solenoid valves.

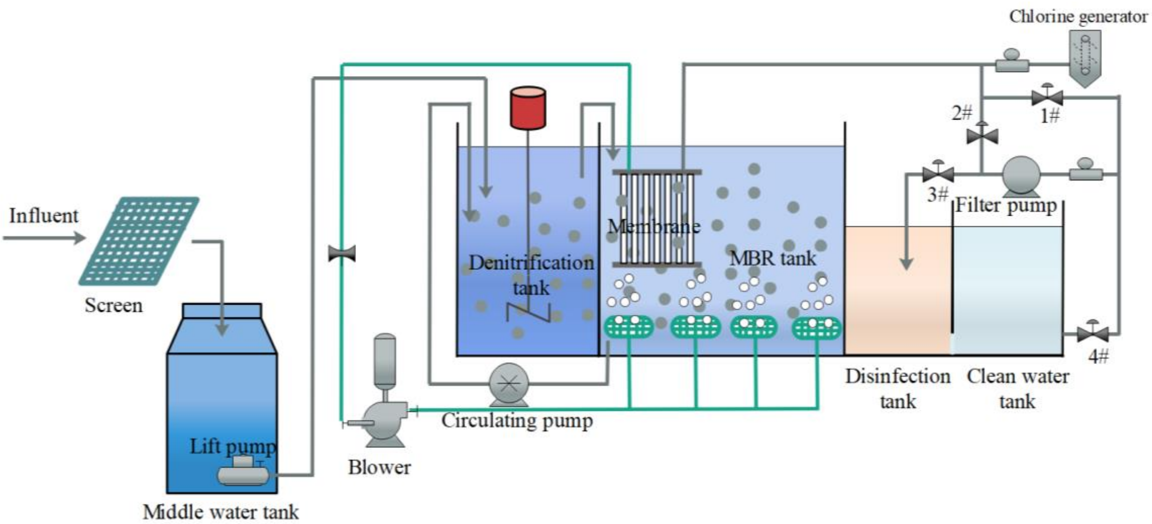

Figure 1. C-MBR campus wastewater reuse unit.

The membrane module is equipped with a membrane backwashing system. When the 2#, 3# solenoid valve opens, chlorine produced by the chlorine machine enters the disinfection pool to prepare cleaning agent NaClO; when the 1#, 3# solenoid valve opens, the automatic backwashing process is opened; and when the 1#, 4# solenoid valve opens, the self-priming pump set up for the membrane module pumps water from the membrane module into the clear water pool.

2.2. Operating Conditions

The experimental unit for water reuse was operated for 96 days, and this study mainly investigated two stages (Stage I and Stage II, respectively): Stage I from 1 day to 58 day, with a sub-total of 58 day, and Stage II from 59 day to 96 day, with a sub-total of 38 day. At each stage, the effects of the operating conditions and characteristics of the influent water on the effluent water quality, including COD and NH_4^+-N, were investigated. Specifically, based on the optimal recirculation ratio (i.e., the ratio of the mixture return flow rate to the influent water volume) of 400%, the effect of intermittent aeration was analyzed in the first stage to control the duration of the blower aeration of the MBR tanks. In the second stage, the effect of the filtration backwash cycle was investigated, and the C-MBR was used to mitigate membrane contamination by rinsing the membrane with a backwash and the formation of a larger shear flow from the aeration of perforated aeration tubes to rinse the membranes during the operation. The two experimental phases were divided into six different operating cycles and four operating cycles (cycles 1–10), respectively. During the operation period, daily samples were taken to determine and record the COD, NH_4^+-N, pH, TN (total nitrogen), TP (total phosphorus), temperature, transmembrane pressure (TMP), and other indicators of the influent and effluent of the reaction tank.

The wastewater used in the experiment was the campus wastewater of the Guilin University of Technology, which included dormitory laundry and shower wastewater, canteen wastewater, and toilet flushing wastewater. It was mainly characterized by a large amount of organic matter and suspended particulate pollutants and good biodegradability (BOD_5 (biochemical oxygen demand)/COD > 0.03) but a low carbon to nitrogen ratio. The highest value of influent COD measured during the experiment reached 236.1 mg/L, the nitrogen volumetric loading (NLR) was 0.02 $g/m^3 \cdot d$, and the characteristics of wastewater quality are shown in Table 1. Sludge for experimental inoculation was obtained from 4000 mL of conventional aerobic sludge and denitrifying sludge from the biological reactor of the Yanshan Town Wastewater Treatment Plant, Guilin City, China, with a concentration of 1894 mg/L. The MBR system adopts a complete sludge retention operation strategy, and the net biomass growth can be ignored; therefore, no sludge recycling is required.

Table 1. Campus wastewater of Guilin University of Science and Technology.

Parametric	The Range of Water Quality Changes	Inflow of Water
CODcr	mg/L	100~240
BOD_5	mg/L	13.6~50.6
TN	mg/L	70~95
TP	mg/L	4~8
NH_4^+-N	mg/L	70~90
turbidity	NTU	47~177
SS	mg/L	65~120
chromaticity	times (multiplier)	50~250
pH	-	7~9
temperature	°C	11~25

2.3. Water Quality Analysis

A certain amount of raw water and the mixture in the biochemical tank was taken and left to stand, then the supernatant was taken and quickly filtered with qualitative filter paper, the C-MBR effluent was filtered through a ceramic membrane without pre-treatment, and the water samples were collected in sampling bottles and placed in a refrigerator at 4 °C. COD and MLSS (mixed liquor suspended solids) were determined using the method described by Zhang et al. [18]; NH_4^+-N, total nitrogen (TN), and TP were detected according to the descriptions of Zhang et al. [19]; pH and temperature were determined using an LB-PHB-4 portable pH thermometer (Leici; Shanghai, China); and dissolved oxygen (DO) was measured using a JENCO MODEL 6010 dissolved oxygen meter (Shanghai Jenco Instruments Co; Shanghai, China). TMP (trans-membrane pressure) was recorded using a digital pressure sensor (Shangyi; Foshan, China).

2.4. Microbiological Analyses

The sludge used for microbiological analyses came from sludge samples at the beginning and end stages of the experiment, sample A and sample B. The sludge samples were sampled and stored in a refrigerator at −20 °C. Microbial diversity was determined through sludge DNA extraction, DNA purity detection, PCR amplification, DNA purification and recovery, and sample delivery for sequencing. Specific experimental steps were performed according to the method described by Xiaoning et al. [20].

2.5. EPs and SMPs Analyses

Extracellular polymers (EPs) and dissolved microbial products (SMPs) were measured in a quantitative sludge mixture collected daily during reactor operation. For EPs, a certain amount of sludge mixture was taken in a centrifuge tube and centrifuged at 4000 rpm for 5 min; the supernatant was poured off, replenished with deionized water, and heated uniformly in a water bath at 80 °C for 0.5 h. Then, it was centrifuged at 5000 rpm for 15 min, and then the supernatant was extracted and filtered through 0.45 nm acetate microfiltration membranes; the filtrate was called EPs, which was characterized by the amount of total organic carbon (TOC). The EPs were characterized by TOC. For SMPs, the quantitative sludge mixture was filtered quickly with filter paper, and then the filter with 0.45 nm acetate microfiltration membrane was characterized by TOC.

3. Results and Discussion

3.1. Processing Performance

3.1.1. Effect of Intermittent Aeration on COD and NH_4^+-N

The changes in COD and NH_4^+-N under the influence of intermittent aeration and the comparison of the removal rate of different intermittent aeration times are shown in Figure 2, and the six different intermittent aeration times are 0.5 day, 1.0 day, 1.5 day, 2.0 day, 2.5 day, and 3.0 day. Figure 2a represents the removal of COD; the influent COD was in the range of 101.91~165.73 mg/L, the COD removal effect was 75.07~89.23%, with an average removal rate of 83.06%, and the effluent COD contents were all below 30 mg/L, with an average effluent COD of 20.54 mg/L, which had a stable effluent COD concentration. Figure 2b represents the removal of NH_4^+-N. The influent NH_4^+-N concentrations range from approximately 44.71 to 84.36 mg/L, and the influent NH_4^+-N concentration was more volatile. During experimental conditions with different intermittent aeration times, the effluent NH_4^+-N compared to the previous experimental conditions of the NH_4^+-N removal effect was better, effluent NH_4^+-N was in the range of 2.69~12.60 mg/L, the average effluent NH_4^+-N concentration was 6.18 mg/L, the highest NH_4^+-N removal rate was 95.26%, and the average removal rate was 90.10%, showing that the experimental stage of the intermittent aeration NH_4^+-N removal effect was good. The concentration of NH_4^+-N in the effluent water meets the water reuse "urban wastewater reuse-water quality for landscape environment" (GB/T18921-2002) [21] and is fully in line with the "urban wastewater reuse-urban miscellaneous water quality" (GB/18920-2002) [22] standards. The comparative analysis in Figure 2c shows that the removal of COD was better at different intermittent times. Compared with other intermittent aeration time intervals, the lowest COD content and the highest average removal rate of 87.71% were observed in the effluent when the intermittent aeration was 2.0 day. An average removal rate of 87.71% was observed in the effluent when the intermittent aeration was 2.0 day. Figure 2d shows a comparison of the removal rate of NH_4^+-N under six intermittent aeration conditions, the average removal rate of NH_4^+-N showed a trend of first high and then declining, and the average removal rate was 87.59% when the intermittent aeration time was 0.5 day, reaching an average maximum removal rate of 93.27% when it was 1.5 day. The average COD removal rate was 87.71% with an intermittent aeration time of 2.0 day. The average removal rate of COD was 87.71% when the intermittent aeration time was 2.0 day. Overall, the C-MBR process had the best NH_4^+-N removal effect at 1.5 day of intermittent aeration. The combined COD and NH_4^+-N removal effect was 78.57% and 93.27% for COD and

NH_4^+-N, respectively, at 1.5 day of intermittent aeration, and 87.71% and 92% for COD and NH_4^+-N, respectively, at 2.0 day. The results showed that the C-MBR had the best removal effect on NH_4^+-N after 1.5 day of intermittent aeration. The results showed that an intermittent aeration time of 2.0 day was able to achieve high COD and NH_4^+-N removal simultaneously.

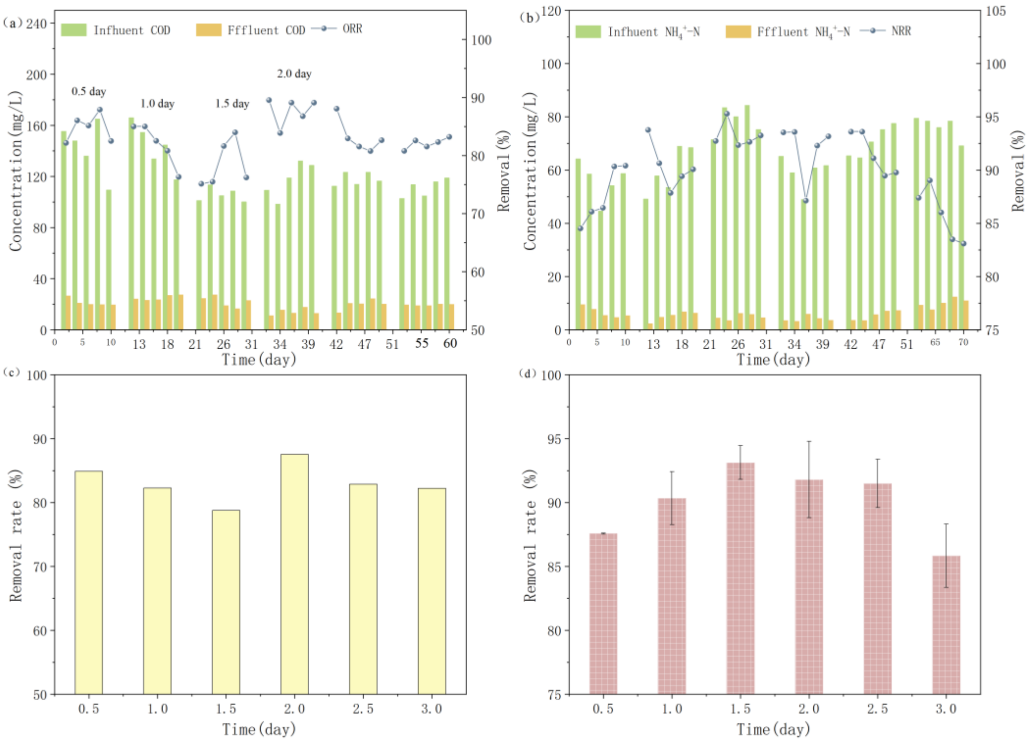

Figure 2. Removal of COD and NH_4^+-N under different intermittent aeration times: (**a**) removal of COD under the influence of intermittent aeration, (**b**) removal of NH_4^+-N, (**c**) comparison of COD removal rates under 6 intermittent aeration conditions, (**d**) comparison of NH_4^+-N removal rates under 6 intermittent aeration conditions.

The data from this study show that the best ammonia nitrogen removal was achieved at 1.5 day of intermittent aeration. Analyzing the causes, the first stage of the experiment was the domestication stage of the microorganisms, in which the nitrifying bacteria in the reactor tank gradually adapted to the campus domestic wastewater and began to multiply. In contrast, it is possible that a large amount of digestate circulates to the pre-reaction zone, the parthenogenetic anaerobic microorganisms in the pre-reaction zone will digest and decompose nitrogen-containing organic matter such as proteins into inorganic ammonia nitrogen, and then a large amount of inorganic ammonia nitrogen is not completely removed by the inorganic ceramic membrane filtration after the bottom refluxes to the main reaction zone, which results in an increase in the amount of ammonia nitrogen in the effluent water. Simultaneously, the relative removal rates decreased. Ammonia nitrogen mainly exists in water as ammonia ions and free ammonia, and its molecular diameter is smaller than the pore diameter of the membrane. Therefore, the membrane's retention of ammonia nitrogen is very small, and the removal of ammonia nitrogen by C-MBR is mainly due to the microbial degradation of ammonia nitrogen in the reaction tank. The aeration time had little effect on the COD removal efficiency. Overall, the best removal of conventional pollutants was achieved using the C-MBR with an aeration time of 1.5 d.

3.1.2. Effect of Filtration Backwash Cycle on COD and NH_4^+-N

The variation in COD with NH_4^+-N and a comparison of the removal rate under different filtration backwash cycles are shown in Figure 3. It can be observed from Figure 3a,b that this experimental phase was carried out after 40 days, during which the COD of the C-MBR influent water fluctuated between 100 mg/L and 184.82 mg/L, and the COD values of the effluent water were all below 30 mg/L, with the highest removal rate of COD being as high as 92.17%, and the average removal rate of COD as high as 85.63%, and the effluent water COD was relatively stable; the COD of the influent water NH_4^+-N fluctuated between approximately 50 and 80 mg/L, the effluent NH_4^+-N was 3.31~10.08 mg/L, the average effluent content was 7.27 mg/L, the maximum removal rate was up to 95.54%, and the average removal rate was 89.94%. In this experimental study, the filter backwash cycle was set to four cycles of 8/2 min, 8.5/1.5 min, 9/1 min, and 9.5/0.5 min. As shown in Figure 3c, changes in the filter backwash time cycle did not have a significant effect on the removal of COD or NH_4^+-N, whereas the C-MBR system had a stable carbon and nitrogen removal effect. The 8/2 min and 8.5 /1.5 min cycles had significantly lower COD removal than the 9/1 min and 9.5/0.5 min cycles, and the 9/1 min cycle possessed an average removal rate of 86.45%; in the 9/1 min filter backwash cycle experiment, the average removal rate of NH_4^+-N was 92.47%, which had a better treatment effect. The results showed that both pollutants had high removal efficiencies when the filtration backwash cycle was 9/1 min. In the 9/1 min filtration backwash cycle, a longer filtration time of 9 min ensures the daily treatment capacity, and the 1 min backwash also slows down the contamination of the membrane module well, coupled with the process slowing down the contamination of the membrane module by continuously blowing the membrane surface. Maqbool et al. [23] achieved 93.3% COD removal in 8/2 min filtration backwash cycle mode and a lower NH_4^+-N removal rate of 53.7%, whereas in our study with the same 10 min cycle, the 9/1 min cycle mode NH_4^+-N removal was significantly higher than that in the above study, probably because of the short hydraulic residence time.

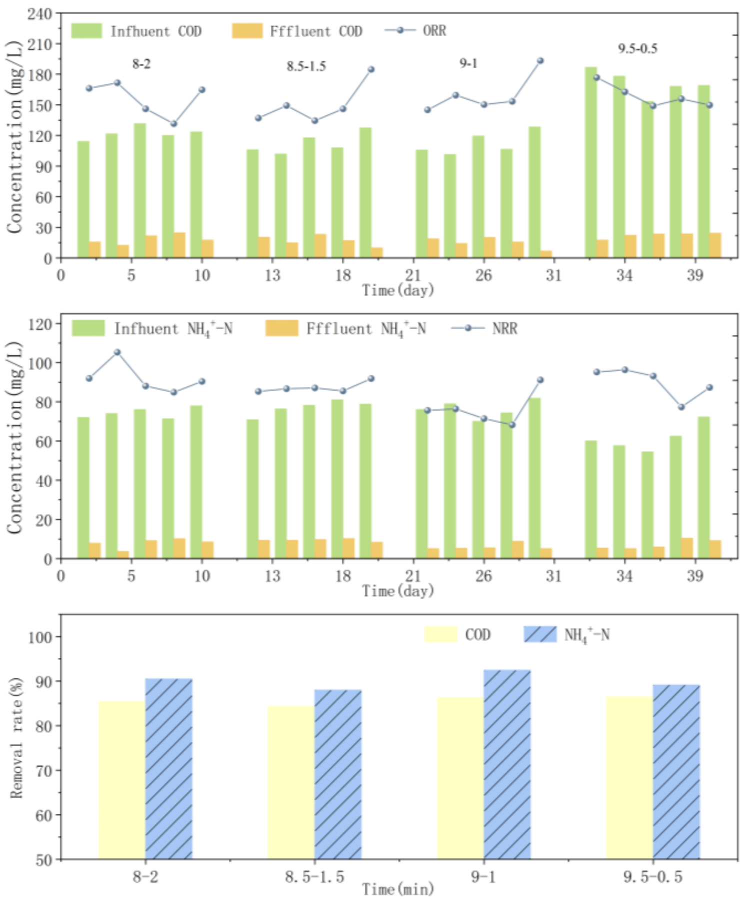

Figure 3. Removal of COD and NH_4^+-N under different filtration backwashing time.

3.2. EPs and SMPs Generation

SMPs and EPs are the main membrane contaminants, leading to reduced permeate flux and increased transmembrane pressure in MBR systems, which in turn affect effluent quality (COD removal, formation of potentially toxic and carcinogenic substances) and functional water reuse with high demands for water reuse [20]. SMPs can be classified according to the stage of bacterial derivation into utilization-associated products of the substrate during the microbial growth process (UAP) and endogenous respiratory processes produced by biomass-associated products (BAPs) [24]. EPs contain bound EPs (EPS_{Bound}) and soluble EPs (EPSs) [23]. Based on the assertion by Laspidou and Rittmann, soluble EPs are the same as SMPs in sludge, and the hydrolysis of bound EPs is the only source of BAPs. A unified model of EPs, SMPs, and active biological units can be plotted (shown in Figure 4) [25]. Effluent SMPs can be as high as 17% of the input COD, which is an important control of wastewater quality and is very important for water reuse projects, while the production of SMPs and EPs is influenced by many factors (e.g., operating parameters and substrate concentration) [26].

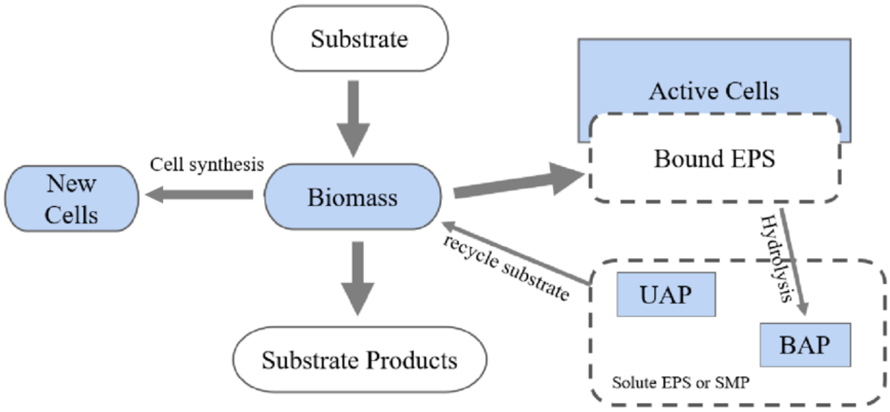

Figure 4. Unified model of EPs and SMPs with active biological units [1,26].

Figure 5 shows the trend graphs of the average EPS_{Bound}, SMPs, and EPs contents for each of the six intermittent aeration times and four filtration backwash cycles. In cycle 1 of the intermittent aeration phase, the average EPS_{Bound}, SMPs, and EPs was 30.03 mg/g, 64.33 mg/g, and 94.36 mg/g, respectively. From cycle 1 to cycle 6 (stage 1), the values of EPS_{Bound} and SMPs increased to 52.39 and 136.03 mg/g, which increased by 42.68% and 52.71%, respectively. The growth rate of EPS_{Bound} and SMPs gradually slowed down in the later stages. From the beginning of cycle 4 (2.0 day of aeration time) to cycle 6 (3.0 day of aeration time), the average growth rates of EPS_{Bound} values were 0.01 and 0.05 mg/g/d, and the average growth rates of SMPs values were 0.13 and 0.45 mg/g/d. Compared with the growth rates of EPS_{Bound} and SMPs at the beginning of the cycle, which were 0.49 and 0.44 mg/g/d, the growth rates of EPs and SMPs after 2.0 day of aeration increased by 42.42% and 52.71%, respectively. The aeration and growth rates of the EPS_{Bound} and SMPs were significantly reduced. This result indicates that, within a certain time frame, the longer the aeration time, the higher the microbial concentration, followed by a decrease in the EPs composition. Subsequently, from cycle 6 to cycle 10 (second stage), the value of SMPs increased by only 5.32%, whereas that of EPS_{Bound} decreased to 46.17 mg/g, a reduction of 11.87%. The decrease in the value of EPS_{Bound} and the increase in the value of SMPs indicate that under the operating conditions of filtration backwashing, the SMPs produced in the system are not due to the leaching of material from dead cells but are produced by the combination of EPs and SMPs. The experimental results of EPs and SMPs production showed that for aeration times below 2.0 day, aeration had little effect on the levels of EPS_{Bound} and SMPs, whereas aeration times above 2.0 day had a significant effect on the levels of EPS_{Bound} and SMPs. As the system was aerated for an extended period, optimizing the filter backwash time at 2.0 day of aeration was effective in controlling membrane contamination, and a filter backwash time of 9/1 min significantly reduced SMPs levels. Small fluctuations in SMPs and EPs were observed in each experimental cycle, which were attributed to the minimization of changes in the sludge characteristics under steady-state conditions.

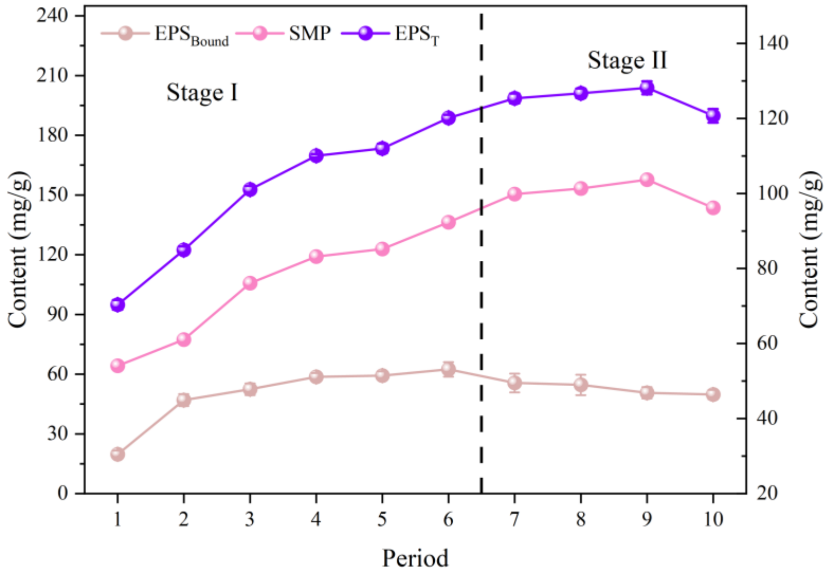

Figure 5. Trends in the average content of EPS$_{Bound}$, SMPs, and EPs.

In the correlation analysis presented in Table 2, there was a strong positive correlation between SMPs and EPS$_{Bound}$ (p = 0.03 < 0.05), indicating that the higher the content of EPS$_{Bound}$ in the entire system, the more EPS$_{Bound}$ was hydrolyzed into SMPs. In addition, EPS$_{Bound}$ showed a positive correlation with COD and C/N ratios, which was the same as that in a study conducted by Mannina et al. [27] on the production of EPs in an MBR reactor at different C/N ratios. This result is similar to that reported by Mannina et al. for EPs production in MBR reactors with different C/N ratios. SMPs were positively correlated with the C/N ratio and negatively correlated with COD, indicating that the C/N ratio in the effluent is also increased at this time. High C/N ratios promoted the removal of COD, which is the same phenomenon as described by Yadu et al. [28].

Table 2. Pearson correlation analysis.

	NH_4^+-N	COD	TP	C/N Ratio	EPS$_{Bound}$
COD	−0.747 *	-	-	-	-
TP	0.611	−0.242	–	–	–
C/N ratio	−0.786 **	0.702 *	−0.445	–	–
EPS$_{Bound}$	−0.477	0.354	−0.330	0.558	–
SMPs	−0.271	−0.023	−0.106	0.208	0.672 *

Notes: * Correlation significant at the 0.05 level (two-tailed). ** Correlation significant at the 0.01 level (two-tailed).

3.3. Microbiological Analysis

Table 3 (BLAST comparison results) and Figure 6 (phylogenetic tree) show that each bacterial species belongs to the same category as the corresponding branch in the phylogenetic tree. The bacteria in the sludge from the C-MBR were mainly *Proteobacteria*, *Acinetobacter*, and *Arcobacter*. From Figure 6, it can be seen that 2 and 3 belonged to the same genus of Aspergillus, 4 and 5 belong to the same genus of Fusobacteria, and 1 belongs to the group of Arcobacter alone.

Table 3. Blast comparison results (The samples were provided by Sangon Biotech, Shanghai, China).

Serial Number	Similarity	GenBank Serial Number	Organisms
1	99%	JQ845763.1	uncultured *Arcobacter* sp.
2	96%	JF833520.1	uncultured *Arcobacter* sp.
3	99%	NR_113622.1	*Simplicispira psychrophila*
4	100%	KT767819.1	*Acinetobacter* sp. K7
5	95%	KJ590189.1	uncultured *Acinetobacter* sp.

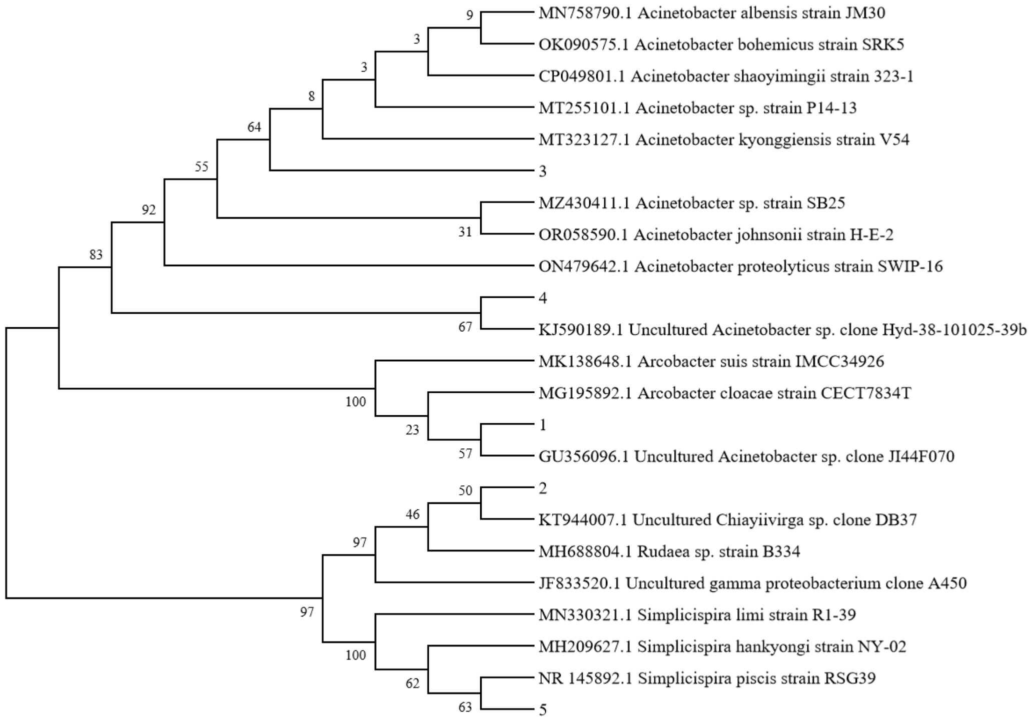

Figure 6. Phylogenetic tree.

Subsequently, the band profiles in the DGGE (denatured gradient gel electrophoresis) images were analyzed using Quantity One 4.6.2 (Bio-Rad Laboratories; Hercules, CA, USA) software, and the relative concentration of each microorganism was derived from the brightness of the bands to obtain the proportion of different bacteria while determining the structure of the bacterial community, thus inferring the dominant bacteria in the activated sludge. The microbial community structure was analyzed using Quantity One software, as shown in Figure 7. The distribution of the bacterial community structure in the sludge within the C-MBR process was as follows: uncultured *Arcobacter* sp. was extinct in sample B, whereas uncultured Gamma proteobacterium was added, as were *Simplicispira psychrophile*, *Acinetobacter* sp. K7, and uncultured *Acinetobacter* sp. In addition, the sludge included a large number of other bacteria with low band brightness, which were numerous but individually small in proportion and were classified in the figure as other categories, accounting for a total of 36.2%; Proteobacteria bacteria and *Acinetobacter* accounted for 50.90% and belonged to the dominant bacteria in the same type of wastewater treatment system [29–31]. For example, Guadie et al. detected mainly ascomycetes, followed by thick-walled bacteria and Acinetobacter with relative abundances of 59%, 12%, and 11%, respectively [32].

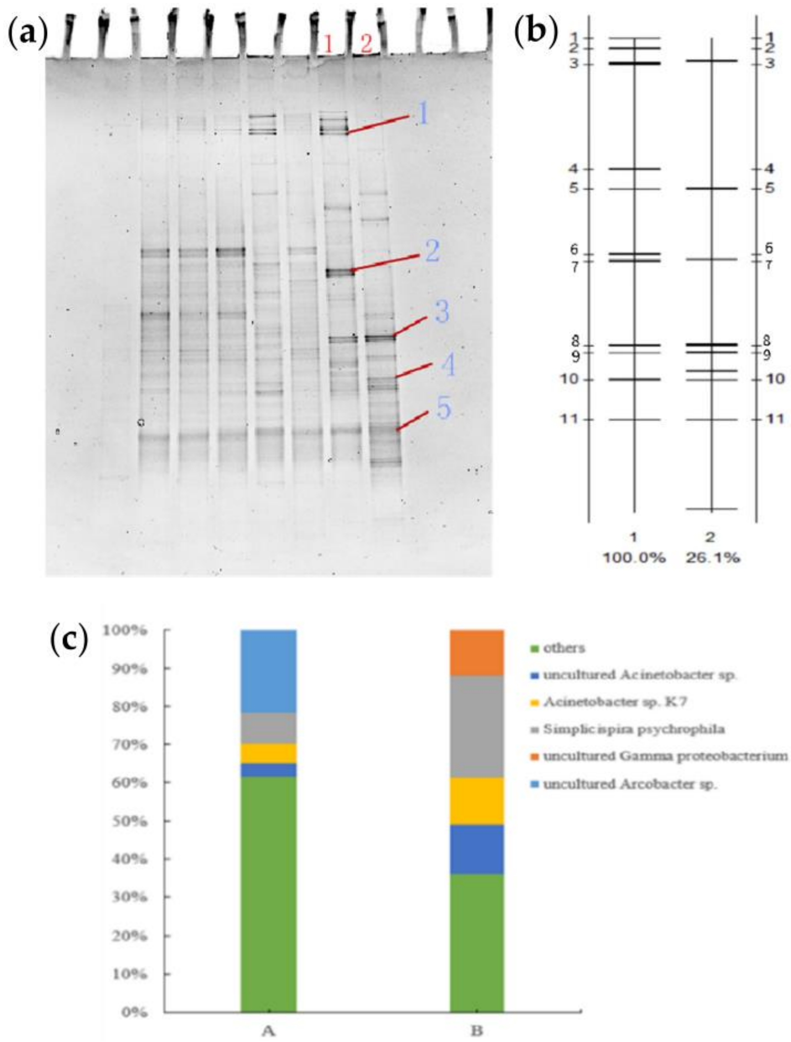

Figure 7. Distribution of microbial community strips and community structure in sludge before and after C-MBR treatment: (**a**) DGGE electrophoresis profiles of the start and end samples of the experiment, the number on each strip represents the electrophoretic intensity, (**b**) Schematic representation of the distribution and intensity of the strips of microbial communities at the beginning and end samples of the experiment, the number on each strip represents the electrophoretic intensity, (**c**) bacterial community structure in sludge before and after C-MBR treatment; A is before treatment, B is after treatment.

4. Conclusions

The C-MBR process can be successfully applied to reuse campus wastewater and has excellent treatment capabilities for difficult organic compounds and nitrogen. However, membrane contamination in the MBR systems causes a decrease in flux and a reduction in membrane performance, which requires frequent chemical cleaning and eventually leads to membrane replacement, thereby increasing the operating costs of the MBR process. The MBR operation mode with intermittent aeration and a filtration backwash cycle was effective in controlling membrane contamination. The COD and NH_4^+-N removal rates were 87.71% and 92%, respectively, with high COD and NH_4^+-N removal rates at an intermittent time of 2.0 day, respectively. Under the 2.0 day intermittent aeration mode, the best nitrogen removal was achieved with a 9/1 min filtration backwash cycle, with an average NH_4^+-N removal of 92.47% and an average COD removal of 86.45%. Although the filtration backwash cycle had little effect on the COD and NH_4^+-N removal, it played a significant role in controlling membrane contamination. An aeration time higher than 2.0 day had a significant effect on the content of EPS_{Bound} and SMPs, whereas the content of

EPS_{Bound} decreased by 11.87% and SMPs increased by only 5.32% under the filter backwash operation condition of 9/1 min, which confirms that the filter backwash operation condition can better control the membrane contamination under the intermittent aeration operation mode. The results of the microbiological analysis showed that the bacteria *Proteobacteria* and *Acinetobacter* were the dominant bacteria in the C-MBR water reuse process, with a proportion of 50.90%, and were the main causes of membrane contamination.

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