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Enhanced nitrogen removal from high-strength ammonia containing wastewater using a membrane aerated bioreactor (MABR)

Arindam Sinharoy, Ji-Hong Min and Chong-Min Chung*

Department of Environmental Science & Biotechnology, Jeonju University, Jeonju 55069, Republic of Korea

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Abstract. This study evaluated the performance of a membrane aerated biofilm reactor (MABR) for nitrogen removal from a high-strength ammonia nitrogen-containing wastewater. The experimental setup consisted of four compartments that are sequentially anaerobic and aerobic to achieve complete nitrogen removal. The last compartment of the reactor setup contained a membrane bioreactor (MBR) to reduce sludge production in the system and to obtain a better-quality effluent. Continuous experiment over a period of 47 days showed that MABR exhibited excellent NH_4^+-N removal efficiency (99.5%) compared to the control setup without MABR (56.5%). The final effluent NH_4^+-N concentration obtained in the MABR was 2.99±1.56 mg/L. In contrast to NH_4^+-N removal, comparable TOC removal values in the MABR and the control reactor (99.2% and 99.3%, respectively) showed that air supply through MABR is much more critical for denitrification than for organic removal. Further study to understand the effect of air supply rate and holding pressure on NH_4^+-N removal in MABR revealed that an increase in both these parameters positively impacted reactor performance. These parameters are related to oxygen supply to the biofilm formed over the membrane surface, which in turn influenced NH_4^+-N removal in MABR. Among the two different strategies to control biofilm over the membrane surface, results showed that scouring for a duration of 10 min on a weekly basis, along with mixing air supply, could be an effective method.
Keywords: ammonia nitrogen; biofilm; membrane aerated bioreactor; membrane bioreactor; nitrogen removal; scouring

1. Introduction

Water is essential to life on Earth as it sustains ecosystems, fosters biodiversity, and provides for basic human requirements (Tortajada 2020 Saikia *et al*. 2022, Patil *et al*. 2023). However, as the population and industrialization grow, available water resources are put under unprecedented burden, causing persistent challenges in wastewater treatment (Sinharoy *et al*. 2022, Im and Gil, 2023). The management of wastewater has become a significant concern in the current environmental sustainability landscape (Lee *et al*. 2023). Among the different pollutants, nitrogen compounds are particularly important in deteriorating the quality of water, therefore, finding effective ways to remove them will require innovative methods (Rahimi *et al*. 2020). An important nutrient for life, nitrogen can have serious negative effects on the environment and human health when it is present in excess amount in water bodies (de Vries, 2021, Gu *et al*. 2023). It can cause eutrophication, oxygen depletion, and the production of toxic nitrogenous byproducts (Chamoli *et al*. 2024, Yun *et al*. 2024). The strict regulatory requirements for nitrogen removal are sometimes beyond the reach of conventional wastewater treatment systems, requiring the development of novel and effective solutions to protect our water supplies.

Due to the diversity of the nitrogenous compounds in wastewater and their varied degrees of reactivity, removing nitrogen from wastewater presents unique challenges (Chai *et al*. 2021). For example, ammonia requires particular environmental conditions and a specific group of microbes to convert it into less toxic forms (Baskaran *et al*. 2020). On the other hand, a different group of microbes and enzymatic mechanisms are involved in the removal process of nitrate and nitrite (Zhang *et al*. 2022). Conventional treatment techniques, such as trickling filters and activated sludge procedures, are effective at removing organic matter but may not be able to remove nitrogen to the desired level (Rahimi *et al*. 2020).

In this context, membrane aerated biofilm reactors (MABRs) offer a possible path for improved nitrogen removal efficiency and represent a paradigm shift in wastewater treatment (Li *et al*. 2023). Combining biological processes with membrane technology, MABRs create a synergistic approach that maximizes nitrogen removal efficiency while reducing energy consumption and operating costs (He *et al*. 2021). Presence of a gas-permeable membrane in the system results in higher oxygen transfer rates as well as it provides a support for biomass retention in the form of biofilm, which intensifies biological treatment inside the reactor (Ravishankar *et al*. 2022). The conversion of different nitrogenous compounds is largely facilitated by different classes of microorganisms, such as denitrifiers and nitrifying bacteria, and the appropriate environment for these different classes of microbes is created by the inherent mechanism involved in oxygen

*Corresponding author, Professor
E-mail: cmchung@jj.ac.kr

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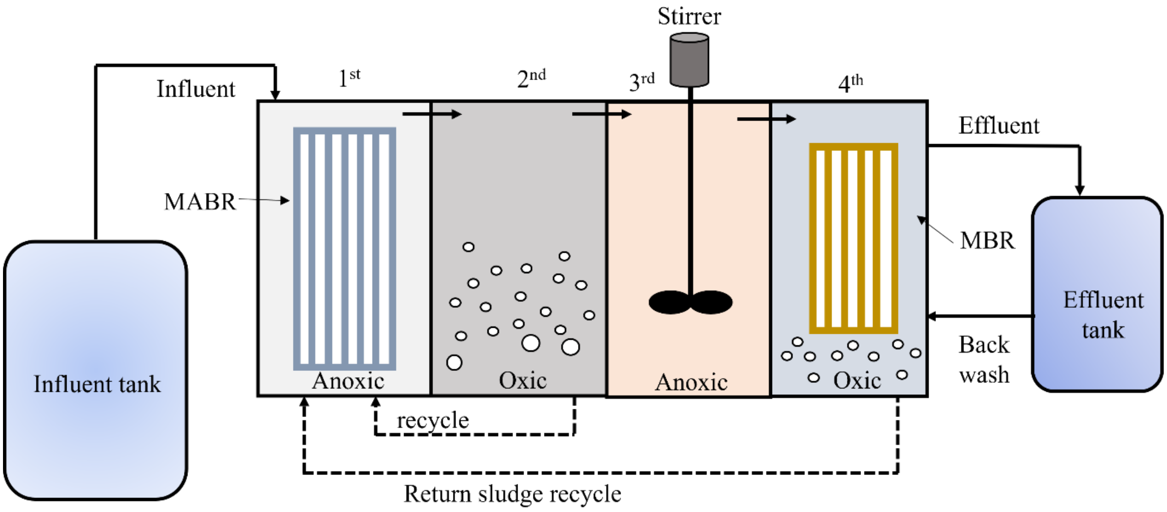

Fig. 1 Schematic diagram of the experimental setup

diffusion through membrane and the biofilm formed over it (Lu *et al*. 2021, Li *et al*. 2023). The effectiveness of MABRs in removing nitrogen species from wastewater depends on a thorough understanding of the underlying physicochemical and biological processes and can hence be used for process improvement.

MABRs have attracted a lot of attention in the past decade as they provide many operational benefits regarding nitrogen removal. The membrane-facilitated high oxygen transfer rates promote the growth and activity of nitrifying bacteria, allowing for selective removal of ammonia as nitrate (He *et al*. 2021). Furthermore, the membrane's selective retention of biomass enables a higher concentration of microorganisms within the reactor, resulting in more compact and space-efficient systems (Uri-Carreño *et al*. 2021). Other general advantages of MABRs over conventional treatment systems include smaller footprint requirements, reduced energy consumption, and lower sludge production compared to traditional treatment methods (Li *et al*. 2023).

Although MABRs show great potential for nitrogen removal, obstacles remain in the way of their general deployment. Most of the existing MABR research is focused on biological sewage treatment processes with low nitrogen concentration (Lu *et al*. 2021), and there is rarely any study to examine the applicability of this technology to treat industrial wastewater containing a high concentration of ammonia nitrogen, such as semiconductor industry wastewater, livestock wastewater, or landfill leachate wastewater (Wang *et al*. 2013, Liu *et al*. 2023). Hence, in this study, a high ammonia nitrogen-containing wastewater, i.e., landfill leachate, was treated using an MABR system. The primary aim of this study is to confirm the effect of applying a gas-permeable membrane to the anoxic tank of the existing conventional biological treatment system to improve nitrogen removal efficiency. The research objectives also include studying the effect of key operational parameters, namely volumetric influent air flowrate, gas pressure, and biofilm thickness control by rough air injection.

2. Materials and methods

2.1 Configuration of experimental setup

The schematic configuration of the experimental setup is depicted in Fig. 1. As seen from the figure, the experimental setup consisted of four compartments with a total volume of 42 L. The experimental setup is made up of Perspex glass. The first and third compartments were anoxic and the second and fourth compartments were aerobic in nature. A MABR consisting of a gas-permeable membrane module is placed in the first anoxic tank. This MABR was connected with an air supply blower. The second tank had a diffuser at the bottom of the tank though which the tank is aerated at 1.5 L/min aeration rate. Mechanical stirrer is provided in the third compartment for proper mixing of the contents inside the compartment. However, no provision for aeration is done to maintain an anoxic environment in this third compartment. A membrane bioreactor (MBR) is placed in the fourth compartment which is also aerated at 1.5 L/min aeration rate to prevent membrane fouling. The membrane has a nominal pore diameter of 0.04 μm. Air diffusers were placed at the bottom of the bioreactors to provide necessary aeration for mixing, biological requirements and membrane scouring.

The wastewater was pumped from a 100 L volume influent tank to the first anoxic tank and moved on to successive tanks through overflow mechanism. A level sensor with automatic flow control mechanism has been provided in the MBR tank (fourth compartment) to maintain the required amount of wastewater in the system. pH sensors were installed in the nitrification tank and reaeration tank, and is set to maintain a pH of 7.3. The pH control mechanism operated under automatically, and whenever the pH of the nitrification tank fells below 7.3, the NaOH pump was set to operate to maintain pH at the desired level. Provision for nitrate recycling from second compartment to first compartment is made in the system. Similarly, a return sludge recycling mechanism is provided between fourth and first compartment. An additional control experimental setup

Table 1 Performance comparison between MABR and control reactor for biological ammonia removal

Parameters	MABR	Control
Gas-permeable membrane area	0.25 m^2	N/A
Suspended growth MLSS	3,987±84 mg/L	3,965±134 mg/L
Suspended growth SRT	35 days	36 days
Effluent NH_4^+-N (Removal efficiency)	2.99±1.56 mg/L (99.5%)	283.1±17.8 mg/L (56.5%)
Effluent TOC (Removal efficiency)	1.67±0.09 mg/L (99.2%)	1.33±0.98 mg/L (99.3%)

is also operated throughout the experimental duration with a similar configuration to the experimental one, except for the presence of the membrane module in the first compartment. The control setup had a stirrer in the first compartment instead of the membrane module. On the other hand, in the case of the MABR reactor, a circulation pump was used to maintain mixing in the first compartment.

2.2 Adsorption of phosphate by La-QQ beads

The bioreactors were fed with synthetic landfill leachate wastewater with a NH_4^+-N concentration of 650 ppm, for potential application to treat high-nitrogen-containing wastewater. The composition of the synthetic wastewater is according to a previous study (Wang *et al*. 2013) and is given as follows: TOC = 200 mg/L, NH_4^+-N = 650 mg/L, NO_2-N = 50 mg/L, NO_3-N = 5 mg/L, T-N = 700 mg/L, T-P = 20 mg/L, pH = 7.0 and temperature = 25℃. The synthetic wastewater was prepared by adding following compounds (g/L): yeast extract (0.04), glucose (0.45), NH_4Cl (2.57), KH_2PO_4 (0.14), NaCl (0.5), $CaCl_2$ (0.014), KCl (0.036), $MgSO_4$ (0.09) and $NaHCO_3$ (0.125). The reactor system had a total HRT of 2 days (48 h). The MLSS concentration inside the reactor was 5,000 mg/L. The activated sludge inoculum was collected from a full-scale MBR receiving municipal wastewater, acclimatized in a fill-and-draw reactor for a month, and passed through a standard sieve of 1 mm mesh opening to remove coarse particles prior to being used as inoculum in the MBR operation. The pH was maintained at 7.3-7.4 and DO levels were 0-1.0 mg/L and 4-5 mg/L, respectively for anoxic (1^{st} and 3^{rd} tanks) and aerobic (2^{nd} and 4^{th} tanks) compartments.

The reactor was operated under continuous mode of operation to study the nitrogen and TOC removal from wastewater. Later, the effect of different process parameters, namely, air flow rate, gas pressure and mixing air injection on the reactor performance, was investigated. Samples are withdrawn every day from the reactor and following filtration with a GF/C filter (0.45/0.2 μm) analyzed for ammonia, nitrate, nitrite, and TOC. The MABR module operating conditions are maintained same as during continuous operation, and in order to eliminate all other variables, inflow water, treated water, backwash, recycle flow are closed off.

2.3 Biofilm control

Biomass tended to accumulate on the membranes, especially at the highest loading rates, and biofilm cleaning was thought to be essential maintain reactor performance. Air sparging is periodically delivered to the lower mold of the membrane module, typically 10 seconds out of every 50 seconds. Coarse bubble aeration was provided by an air sparger attached along the bottom of each of the gas-permeable membrane module. The TS (total solids) concentration of the biomass attached to the membrane was periodically measured according to the change in air sparging injection cycle and intensity.

2.4 Analytical methods

Analysis of ammonia, nitrate and nitrite were performed using an ion chromatograph (IC, Model Ion chromatography-mass spectrometer, Metrohm). Total organic carbon (TOC) analysis was performed using a TOC analyzer (TOC, TOC-5000A, Shimadzu, Japan). All samples were filtered using a 0.2 μm GFC filter prior to their analysis. pH was measured using a pH meter (Model ST300, Ohaus). For biomass analysis, the MABR module was taken out of the first tank following completion of an experiment, placed in a separately prepared water tank, and the biofilm attached to the membrane surface was shaken off with a brush. Following this procedure, the sludge was allowed to settle as much as possible, and TSS and VSS were measured using standard method (APHA 2005).

3. Results and discussions

3.1 Performance of the MABR system compared with conventional biological system

The experimental data from both the MABR and control bioreactor systems, each with a volume of 42 L, presented a clear picture of their respective capabilities in removing NH_4^+-N and TOC from wastewater (Table 1). Both systems operated with comparably high mixed liquor suspended solids (MLSS) concentrations and similar sludge retention times (SRT), indicating that the key difference in performance was not related to biomass concentration but rather to the operational and technological advantages of the MABR system. A significant difference was observed in the removal of NH_4^+-N among both the reactors. The MABR system demonstrated a removal efficiency of 99.5%, with a very low effluent concentration of 2.99±1.56 mg/L, significantly outperforming the control system, which had a removal efficiency of 56.5% and an effluent concentration of 283.1±17.8 mg/L (Table 1). This stark contrast underscores the MABR system's superior capacity for ammonia nitrogen removal from wastewater. The superior ammonia nitrogen removal efficiency observed in the MABR system can be attributed to the enhanced oxygen transfer capabilities of the gas-permeable membrane (Abdelfattah *et al*. 2024). This feature likely supports a more robust and efficient nitrifying bacteria population, facilitating the conversion of NH_4^+-N to less harmful nitrogen forms (Gilmore *et al*. 2013). The high NH_4^+-N removal efficiency highlights the potential of MABR technology in treating high-ammonia wastewater streams, where conventional systems may struggle to meet the regulatory standards. The MABR system's operational benefits extend beyond pollutant removal efficiencies. The membrane's role in providing direct oxygenation to the biofilm creates an optimal environment for aerobic microbial activity, contributing to the system's overall efficiency and potentially reducing energy consumption compared to conventional aeration methods.

The MABR system achieved an almost identical TOC removal efficiency (99.2%) to that of the control system (99.3%), with effluent TOC concentrations of 1.67±0.09 mg/L and 1.33±0.98 mg/L, respectively (Table 1). This marginal difference indicates that both systems are highly effective in degrading organic compounds, with the MABR system showing a slight advantage in terms of consistently low effluent TOC concentration. The nearly equivalent high efficiency in TOC removal by both systems suggests that the presence of the gas-permeable membrane in the MABR does not significantly impact the removal of organic carbon beyond the capabilities of conventional systems. This finding implies that both systems can effectively support the microbial degradation of organic matter, a crucial step in wastewater treatment. Hence, the comparative analysis of the MABR and control bioreactor systems revealed that while both processes are highly effective in removing TOC from wastewater, the MABR system exhibits a significantly higher efficiency in removing ammonia nitrogen. These findings underscore the value of MABR technology in addressing specific challenges in wastewater treatment, particularly in the management of high-strength ammonia wastewaters, offering a compelling solution for improving environmental sustainability and compliance with wastewater discharge regulations.

3.2 Role of the gas-permeable membrane and biofilm in the MABR process

The study presented a comparative data on NH_4^+-N concentrations across different compartments of the MABR and control wastewater treatment systems (Fig. 1). The MABR system demonstrated significantly higher ammonia nitrogen removal efficiency, achieving complete removal in the effluent, compared to the control system which left a considerable NH_4^+-N concentration (197 mg/L) in the effluent. The MABR system significantly reduced NH_4^+-N concentration to 106.48 mg/L compared to 289.72 mg/L in the control (Fig. 2a). This reduction was facilitated by the biofilm formed on the surface of gas-permeable membrane within the MABR system, indicating early-stage nitrification. NH_4^+-N concentrations were progressively reduced across the treatment stages in the MABR system, ultimately achieving zero NH_4^+-N in the effluent. In contrast, the control system showed much less efficiency in NH_4^+-N removal throughout the four stages. The MABR system's gas-permeable membrane supplied oxygen at a concentration of 20.9%, with the exhaust oxygen concentration measured at 16.1%, indicating an average of 4.6% oxygen consumption by the biofilm (data not shown).

This consumption rate underscores the biofilm's active role in the nitrification process, facilitated by the presence of dominant nitrifying microorganisms. The superior performance of the MABR system in ammonia nitrogen removal can be attributed to the synergistic effect of the gas-permeable membrane and the biofilm. The oxygen consumption data reveals that the biofilm efficiently utilized the supplied oxygen for the nitrification process, significantly enhancing NH_4^+-N removal. The presence of a nitrifying biofilm on the gas-permeable membrane in the anoxic-1 compartment suggests that nitrification begins early in the treatment process, facilitating a more comprehensive reduction of NH_4^+-N as the wastewater progresses through the system. This is particularly notable given the anoxic conditions, highlighting the membrane's role in creating a microenvironment conducive to nitrification in the first tank (Anoxic-1).

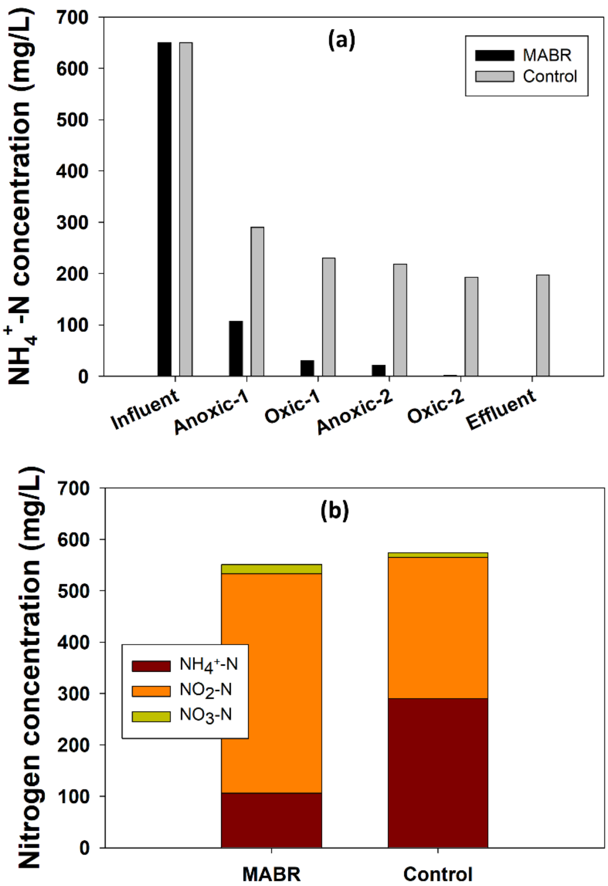

Fig. 2 (a) Comparison between ammonia nitrogen concentration in the influent, different tanks and effluent for MABR and control reactor. (b) Comparison between different nitrogen compounds in anoxic-1 tank for MABR and control reactor

This higher nitrification rate in MABR is also supported by the nitrogen compounds speciation in the first compartment of both systems (Fig. 2b). The NH_4^+-N, NO_2-N and NO_3-N concentrations for MABR were 106.5, 426.6 and 18.1 mg/L, respectively, whereas for control reactor, these values were 289.7, 275.2 and 8.9 mg/L. These relative concentrations of different nitrogen compounds indicate that although the total nitrogen value may be close enough (551.2 and 573.9 mg/L, respectively, for MABR

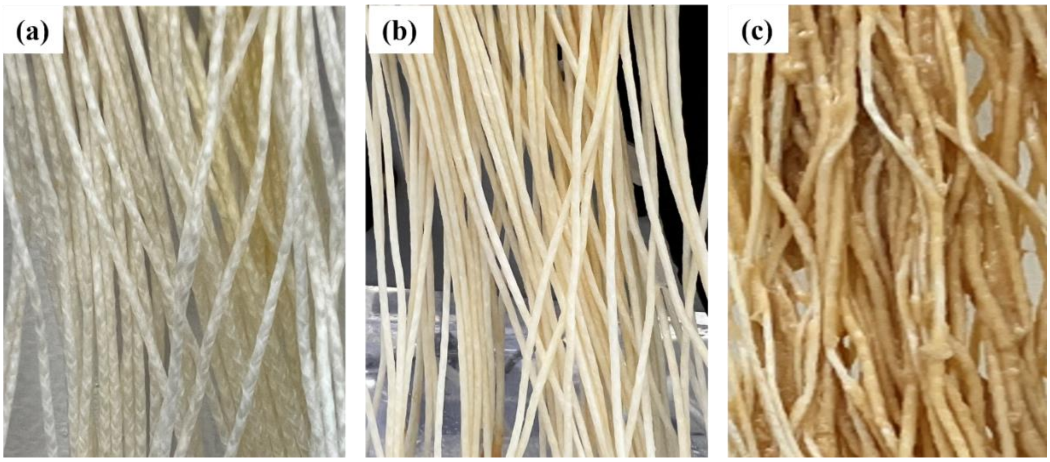

Fig. 3 Images of biofilm formed over membrane surface on (a) day 0, (b) day 7, and (c) day 25 in MABR

Table 2 The volatile and total suspended solids concentrations in biofilm formed over membrane surface in MABR on different days of operation

	Day 0	Day 7	Day 25
VS/TS	NA	69.4%	72.5%
TS mg/m^2 (membrane area)	NA	6.95	18.77

and control system), but the rate of nitrification in MABR-based system is much higher which made all the difference between their relative performance.

The observed oxygen consumption by the biofilm indicates a highly efficient oxygen transfer from the gas-permeable membrane to the biofilm, optimizing conditions for nitrifying bacteria (Ravishankar *et al*. 2022). This efficiency not only supports the nitrification process but also suggests a reduced energy requirement for aeration compared to traditional systems (He *et al*. 2021). The findings underscore the importance of biofilm management and the potential for MABR technology in treating high-strength ammonia wastewaters. The ability to achieve significant NH_4^+-N removal under anoxic conditions suggests that MABR systems can be effectively integrated into wastewater treatment processes to meet stringent discharge standards, especially for industries with high ammonia loads.

3.3 Role of biofilm on the surface of the gas permeable membrane in the MABR process

The study focused on the dynamics of biofilm growth on the gas-permeable membrane in a Membrane Aerated Biofilm Reactor (MABR) and its implications for the treatment process, specifically regarding total organic carbon (TOC) and ammonia nitrogen (NH_4^+-N) removal efficiencies. Fig. 3 shows the biofilm formed over the membrane of MABR on different days of operation. At the start of operation, the absence of biofilm (TS on biofilm = 0 mg/m^2) coincided with TOC and NH_4^+-N removal efficiencies of 99.66% and 88.66%, respectively. Seven days into the operation, the biofilm's TS increased to 6.95 mg/m^2. Despite the biofilm formation, TOC removal efficiency remained stable at 99.66%, while NH_4^+-N removal efficiency slightly decreased to 86.45%. The volatile solids to total solids ratio (VS/TS) was 69.4%, indicating a predominance of organic material within the biofilm. By day 25, the biofilm's TS further increased to 18.77 mg/m^2, with a VS/TS ratio of 72.5% (Table 2). This stage of biofilm maturity was associated with a slight improvement in TOC removal efficiency (99.77%) and a remarkable increase in NH_4^+-N removal efficiency to 100%. The progression of biofilm development on the gas-permeable membrane plays a critical role in the MABR process, significantly impacting the system's ability to remove NH_4^+-N from the effluent. Initially, the absence of biofilm correlated with lower NH_4^+-N removal efficiency. As the biofilm developed, a slight decrease in NH_4^+-N removal efficiency was observed on day 7, which could be attributed to the transitional adjustments within the microbial community (Table 2). However, by day 25, the biofilm's maturity facilitated complete NH_4^+-N removal, illustrating the biofilm's essential role in achieving optimal nitrification. The increase in the VS/TS ratio from 69.4% to 72.5% between days 7 and 25 indicates a higher proportion of organic material within the biofilm, likely due to an increase in microbial mass. This increase in organic content reflects a more active and diverse microbial community, which is essential for the complex processes of organic degradation and nitrification. The enhanced NH_4^+-N removal efficiency at day 25 can be attributed to the enriched presence of nitrifying bacteria within the mature biofilm. The study highlights the importance of biofilm management in MABR systems. The observed trends suggest that operators need to consider the biofilm's growth and maturity stages to optimize system performance, especially for NH_4^+-N removal. Strategies to encourage the rapid establishment and stabilization of biofilm could improve system efficiency and reliability. The study underscores the pivotal role of biofilm on the gas-permeable membrane in the MABR process, demonstrating its critical impact on NH_4^+-N removal efficiency. As the biofilm matures, its capacity to facilitate complete NH_4^+-N removal significantly improves, highlighting the necessity of effective biofilm management in optimizing wastewater treatment outcomes (Miura *et al*. 2024).

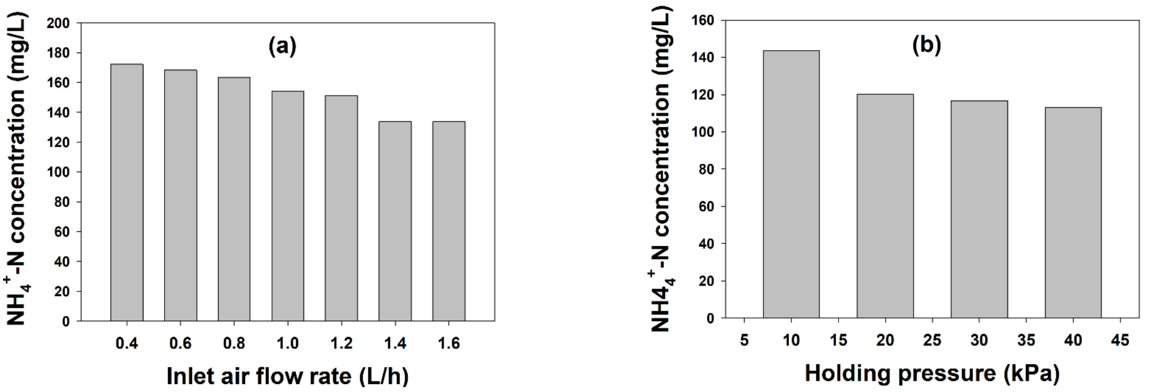

Fig. 4 Effect of (a) inlet air flow rate and (b) gas holding pressure on ammonia nitrogen removal in MABR

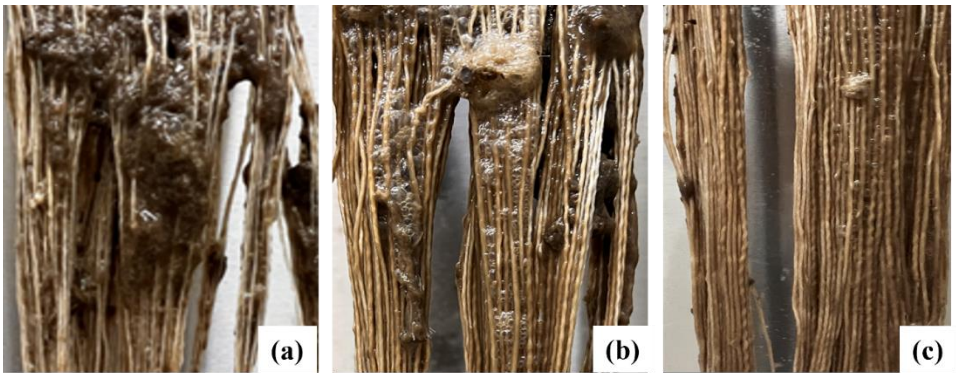

Fig. 5 Biofilm formed over membrane surface under (a) control condition (without mixing air and scouring), (b) with mixing air 10 sec On/50 sec Off (900 mL air/min), and (c) with combined scouring 10 min once/week (900 mL air/min) and mixing air 10 sec On/50 sec Off (900 mL air/min)

3.4 Effect of inlet air flow rate and holding pressure on ammonia nitrogen removal

The effect of different inlet air flow rate to the MABR and holding pressure on ammonia removal was studied (Fig. 4). The results showed that with an increase in inlet flow rate led to increased ammonia nitrogen removal. The effluent NH_4^+-N concentration reduced from 172.2 mg/L at a 0.4 L/h air flow rate to 133.7 mg/L at a 1.4 L/h air flow rate (Fig. 4a). Further increase in air flow rate to 1.6 L/h did not improve the MABR performance, and almost the same effluent NH_4^+-N concentration was obtained at this air flow rate. Similarly, the increase in air holding pressure resulted in improved NH_4^+-N removal from wastewater. Among the different experimental conditions, the lowest effluent NH_4^+-N concentration of 113.1 mg/L was achieved at 40 kPa holding pressure, which was 21% less than the value obtained at 10 kPa (Fig. 4b). Both these experiments indicate that an increase in oxygen concentration or its supply to the biofilm over the surface of the MABR have significant positive impact on the ammonia nitrogen removal performance. The increase in holding pressure also helps in better oxygen transfer due to higher oxygen solubility at elevated pressure (Terada *et al*. 2006). This better oxygen supply promotes aerobic conditions in the biofilm, which is favorable for ammonia oxidation (nitrification). Sufficient oxygen supply is essential for sustaining nitrifying bacteria activity, which converts ammonia to nitrite and then to nitrate (Li *et al*. 2023). These results showed that further improvement in the MABR performance with regards to ammonia removal could be achieved by optimizing the oxygen (air) supply conditions.

3.5 Biofilm control on the surface of the gas permeable membrane with mixing air and air scoring in the MABR process

Biofilm control has been identified as an important parameter in the long-term operation of the MABR (Syron and Casey 2008). It was observed that the biofilm control events did have an impact and the nitrification pathway. Two different strategies were taken to control the biofilm growth on the surface of membrane module, namely, mixing air and mixing air with periodic scouring. The impact of these strategies on biofilm formation is shown in Fig. 5. The biofilm formed under control condition, i.e., without any mixing air or scouring, showed highest amount of biofilm formation which could only be controlled to a limited extent by using the mixing air strategy. However, the addition of scouring for 10 min duration once every week along with mixing air supply created the best biofilm condition. This is due to the removal of excess biofilm on a weekly basis, which prevented a thick and heavy biofilm formation. Such biofilm control using intermittent scouring is supported by previous works as well (Syron and Casey 2008, Bunse *et al*. 2023). This result is significant for long-term operation of MABR system, as overgrown biofilm creates a lot of problem in terms of oxygen diffusion and consequently nitrogen removal performance. A thin biofilm is always preferable for better MABR performance as it have better oxygen transfer, better nutrient distribution, better microbial activity, and prevent membrane fouling, thud providing better operational stability. For example, Bunse *et al*. (2023) reported that high-frequency scouring resulted in better ammonia and total nitrogen removal at high nitrogen loading conditions. The change in microbial community composition due to the nature of scouring is also reported. A relatively higher abundance of nitrifiers and denitrifiers in normally-scoured and non-scoured biofilms in MABR resulted in their better performance in terms of nitrogen removal compared to aggressive scouring, which resulted in low concentrations of important nitrogen-converting microorganism leading to poor performance (Mehrabi *et al*. 2020).

4. Conclusions

The results from the study demonstrated the superior performance of MABR for nitrogen removal from a high-nitrogen containing wastewater in comparison to control reactor with suspended biomass. Although the TOC removal was relatively similar in both MABR and control reactor, the ammonia nitrogen removal was 38.8% higher in MABR. Almost a complete NH_4^+-N removal could be achieved after 47 days of continuous operation using MABR. The better results in MABR are attributed to the enrichment of nitrifying bacteria in the biofilm formed over the membrane surface in MABR as indicated by the increase in VS/TS ratio from 69.4% to 72.5%. Effect of two key parameters related to oxygen supply to the membrane, i.e., inlet air flow rate and holding pressure, on ammonia removal was significant. The ammonia nitrogen removal from wastewater improved with increase in inlet air flow rate and air holding pressure as it creates better oxygen supply conditions for biofilm formed over the membrane surface. Finally, study with different biofilm control strategy revealed that intermittent scouring (on weekly basis for 10 min) along with mixing air supply could effectively control the excessive growth of biofilm and help in achieving stable reactor performance over a prolong period of time. Future research in this area should include experiment with real landfill leachate to evaluate its treatment potential using MABR system. Additionally, further research could focus on optimizing the operational parameters of MABR systems, including membrane surface area, biofilm thickness, and oxygen supply rates, to enhance treatment efficiency. Additionally, exploring the microbial community dynamics within the MABR biofilm could provide insights into improving the stability and resilience of the nitrification process.

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