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Development of quorum quenching cell entrapping carrier for mitigating membrane fouling in MBR

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Abstract. In the membrane bioreactor (MBR) process, problems such as performance deterioration due to membrane fouling, Excessive energy and chemical usage. This study aimed to develop a cell-entrapping carrier (CEC) using the quorum quenching (QQ) mechanism to inhibit fouling in MBR reactors. And this study aimed to develop a strategic plan for mitigating biofouling and reducing operational costs through the application of QQ-CEC. A solution comprising polyvinyl alcohol (PVA) and sodium alginate (SA) with *Rhodococcus sp. BH4* was subjected to 1st and 2nd cross-linking reactions to complete CEC formation and evaluated its physical performance. Subsequently, definiting three types of conventional MBR with no CEC (cMBR), vacant-CEC (vMBR) and QQ-CEC (QMBR) were operated to investigate the carrier effect. The QMBR extended the operation duration to reach permissible TMP by more than 2.54 times that of the MBR and 1.35 times that of the vMBR. Furthermore, it has been established that biofouling can be mitigated through the application of QQ, resulting in a reduction of chemical usage by approximately 39.2%. Following operation of the QMBR, confirming that QQ-CEC inhibited biofouling. The extracellular polymeric substances (EPS) generated on the membrane surface was found to be 0.32 $mg \cdot L^{-1} \cdot day^{-1}$ per cumulative permeate volume that was less than 4 times and 2 times lower compared to the cMBR and vMBR. However, no significant differences in effluent quality were observed, as QQ did not have a substantial impact on the alterations in microbial communities. This study addresses membrane bioreactor (MBR) fouling and optimizes process operations, thereby establishing a foundation for scale-up.
Keywords: biofouling; cell entrapping carrier; EPS; MBR; quorum quenching; TMP

1. Introduction

In the MBR process, contaminants are treated using activated sludge microorganisms and permeate water is filtered by membrane that is utilized at lots of water treatment processes (Shadia *et al*. 2023, Tewfik *et al*. 2023). A membrane is installed in the aerobic tank, and the filtered treated water is discharged (Meng *et al*. 2017, Brik *et al*. 2006). Since the treated water is filtered and discharged, a secondary clarifier is not required, saving land equivalent to the area. Additionally, it is possible to maintain a high concentration of MLSS so that the treatment is more effective about nutrients removal than that of existing advanced processes, and the SRT can be maintained long due to the small amount of excess sludge (Chen *et al*. 2011, Lee and Kim 2013). However, the MBR process encounters significant challenges associated with membrane fouling caused by microorganisms and suspended solids. Membrane fouling phenomenon leads to heightened energy consumption by pumps, as the operational duration extends due to increasing transmembrane pressure. Furthermore, it necessitates increased energy expenditure for excessive aeration aimed at mitigating fouling. Such energy demands are directly correlated with an escalation in Scope 2 greenhouse gas emissions. Additionally, the maintenance of membrane surfaces requires the utilization of substantial quantities of cleaning chemicals (Kim *et al*. 2024). These problems increase the operating cost of the process.

In order to improve the fouling problem of the MBR process, the cause of fouling must be identified. QS mechanism represents a collective behavior exhibited by microorganisms in response to the detection of signaling molecules that exceed a specific concentration threshold. In Gram-negative microorganisms, the QS mechanism is activated by signaling molecules known as N-acyl homoserine lactones (AHLs) (Song *et al*. 2023). During this process, these microorganisms synthesize polymeric substances that facilitate the formation of stable communities, referred to as EPS and soluble microbial products (SMP) (Du *et al*. 2020, Luna *et al*. 2014). The accumulation of EPS and SMP on the surface of a membrane is referred to as biofilm formation. The presence of a biofilm leads to fouling, which occurs as a result of pore blockage and the accumulation of a cake layer on the membrane (Bin *et al*. 2008, Jiang *et al*. 2013). As it accumulates, fouling of the membrane occurs. To mitigate this problem, backwashing and maintenance cleaning with low-concentration chemicals are performed. However, when the TMP eventually reaches the permissible pressure,

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a high-concentration chemical cleaning process must be performed.

Many prior studies have been conducted to alleviate fouling in the MBR process, and among them, various studies have been conducted on QQ, which utilizes microorganisms or enzyme to inhibit the QS mechanism (Huang *et al*. 2016). QQ includes three methods to reduce QS mechanism of microbial communication (Lee. 2013): inactivation of signal generators, derangement of signal receptors, and degradation of signal molecules (Fig. 1). The method of signal molecule degradation has been employed in numerous studies, primarily through the decomposition of AHL by QQ bacteria or QQ enzymes. However, QQ enzymes exhibit limited stability within the reactor environment, prompting a significant focus on research utilizing QQ bacteria (Nam *et al*. 2015, Islam *et al*. 2022). In particular, various studies have been conducted to suppress fouling by immobilizing QQ bacteria on carriers manufactured using polymeric organic materials and injecting them into the reactor of the MBR process (Rose *et al*. 2024). According to a study, increased quantities of QQ bacteria have been found to enhance the effectiveness of biofouling control. The use of QQ MBR has shown a substantial reduction in energy consumption for aeration and filtration around 40–60% in comparison to traditional MBR systems. The mitigation of membrane fouling through QQ mechanism increase the membrane's utilizing period by enhancing the chemical cleaning cycle. This highlights the economic viability of QQ MBR for practical implementation in the field (Lee *et al*. 2018). In certain research, in lab-scale MBR experiments, it was observed that QQ-sheets, with a thickness of 0.5 mm, exhibited a more pronounced physical cleaning effect compared to QQ-beads, which had a diameter of 3.5 mm. This difference can be attributed to the interaction of electrons with the membrane surface, occurring both from the inside and outside of the hollow fiber bundles (Nahm *et al*. 2017, Iqbal *et al*. 2021).

In this study, CEC was produced utilizing the well-known QQ bacterium *Rhodococcus sp*. *BH4* (*BH4*), and its efficacy was systematically assessed. According to Huang *et al*. (2022), *BH4* exhibits exceptional degradation performance for AHLs with short to medium carbon chain lengths, and it has been reported to biodegrade AHLs stably within the range of C4 to C14. QQ-CEC to the MBR process was investigated to mitigate biofouling, with a comparative analysis of the TMP increase rate. Furthermore, an analysis of EPS, which are known to contribute to fouling, was conducted to assess the inhibitory effects of QQ bacteria on EPS production. The fouled membrane underwent a stepwise cleaning procedure to quantify both physical and chemical filtration resistance, and the underlying causes of fouling were elucidated by correlating the findings with the results of the EPS analysis. The energy consumption of the pump and the chemical usage associated with the MBR process were standardized to a 100 m^3 MBR system. Subsequently, the operating costs were estimated and compared. This study aimed to develop a strategic plan for mitigating biofouling and reducing operational costs through the application of QQ-CEC.

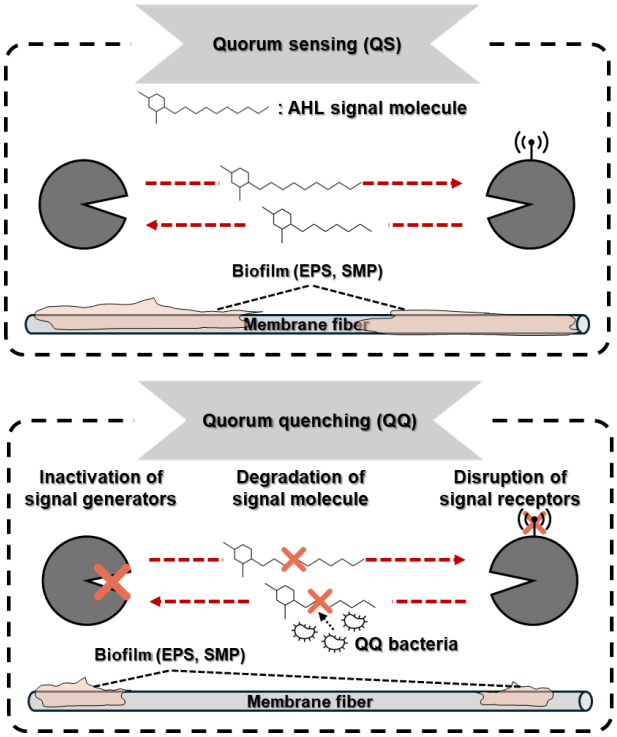


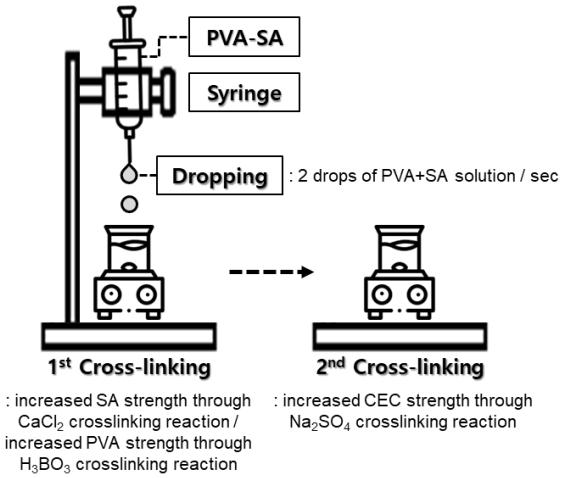
Fig. 1 Mechanism of quorum sensing and quorum quenching

Additionally, it proposes a scale-up plan for the MBR process informed by the findings of this research.

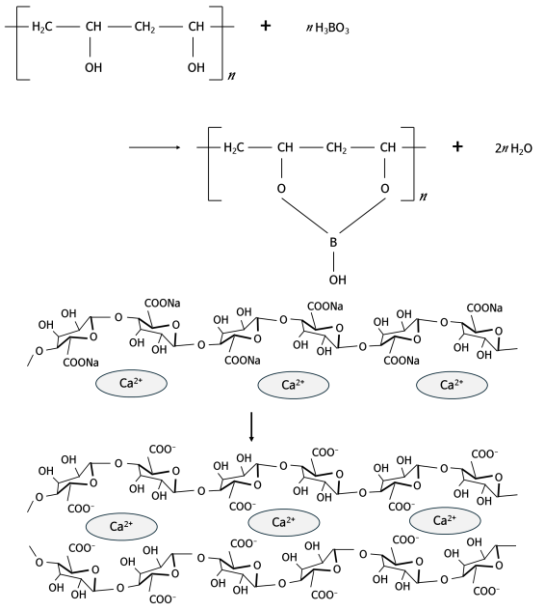
2. Materials and methods

2.1 Preparation of CEC

Previous studies have demonstrated that a carrier with a stable and robust structure can be synthesized by employing a double cross-linking reaction of a PVA and SA mixed solution in calcium chloride ($CaCl_2$) and boric acid (H_3BO_3) solutions (Hua *et al*. 2010, Lu *et al*. 2021, Takei *et al*. 2011). The PVA and SA were injected into distilled water and stirred at 120°C for approximately 4 hours to ensure complete dissolution, followed by cooling to around 40°C. Furthermore, Luria-Bertani (LB) solution inoculated with *BH4* was partitioned into four 50 mL conical tubes and centrifuged at 2000 rpm for 20 minutes. The supernatant was removed, and 5 mL of distilled water was introduced into each tube, vortexed, and subsequently combined with the cooled PVA-SA solution that the concentration of microbials becomes 20mg/mL solution, ensuring thorough mixing. Subsequently, employing a CEC production apparatus as per the parameters delineated in Table 1, the PVA-SA solution was incrementally added to the first cross-linking solution for the reaction, then transferred to the second cross-linking solution for the completion of CEC formation (Fig. 2(a)) (Islam *et al*. 2020). The first cross-linking increased SA strength through CaCl2 cross-linking reaction and PVA strength through H_3BO_3 cross-linking reaction. Cross-linking mechanism is explained by Fig. 2(b).



(a) A schematic diagram of the CEC manufacturing process



(b) Mechanism of first cross-linking

Fig. 2 System and mechanism of manufacturing cell-entrapping carrier

Table 1 Preparation methods of cell entrapping carriers

Sol. Types	PVA (%)	SA (%)	CL solutions		CL reaction time (hours)	
			1st	2nd	1st	2nd
Case #1	6	1	4% $CaCl_2$ + 7% Boric acid	0.5 M Na_2SO_4	0.5	2
Case #2					2	4
Case #3	8				0.5	2
Case #4					2	4

Table 2 Experimental evaluation and scoring procedure of CEC physical and swelling stability

Categories		Physical strength	Swelling stability
Equipment		Centrifuge	Jar-tester
Evaluation methods		- 20 mL distilled water - 20 ea. CEC in conical tube - 4000 rpm, 30 mins	- 1.0 L distilled water - 10 mL CEC in jar - 85 rpm, 15 days
Score	Completely broken	0	0
	Partially broken	25	25
	Not broken	50	50

Second cross-linking was conducted to decrease the duration of the first cross-linking process, thereby minimizing cellular damage caused by the saturated boric acid solution.

2.2 Evaluation methods of physical performance

The physical stability of the prepared CEC was assessed through strength testing via centrifugation and swelling stability in distilled water (Ahmed *et al.* 2020). Twenty CEC samples were introduced into a conical tube containing 20 mL of distilled water and centrifuged at 4000 rpm for 30 minutes using a centrifuge Combi R515 (Hanil Scientific Inc., Korea). Furthermore, to assess the expansion stability upon introduction to the MBR, a mixture of 1 L of distilled water and 10 mL of CEC was subjected to continuous stirring at 85 rpm for approximately 15 days in a jar-tester. The detailed experimental procedures and assessment methods are presented in Table 2.

2.3 Operation of the lab-scale MBR process

This experiment employed a mini module made of microfiltration membrane Hisep MF (Synopex Inc., Korea) that is made polyvinylidene fluoride (PVDF). The module has a pore size of 0.1 μm and a surface area of 283 cm^2. The configuration of the MBR device is illustrated in Fig. 3. It is configured via the programmable logic controller (PLC) panel to enable automated control functions, such as

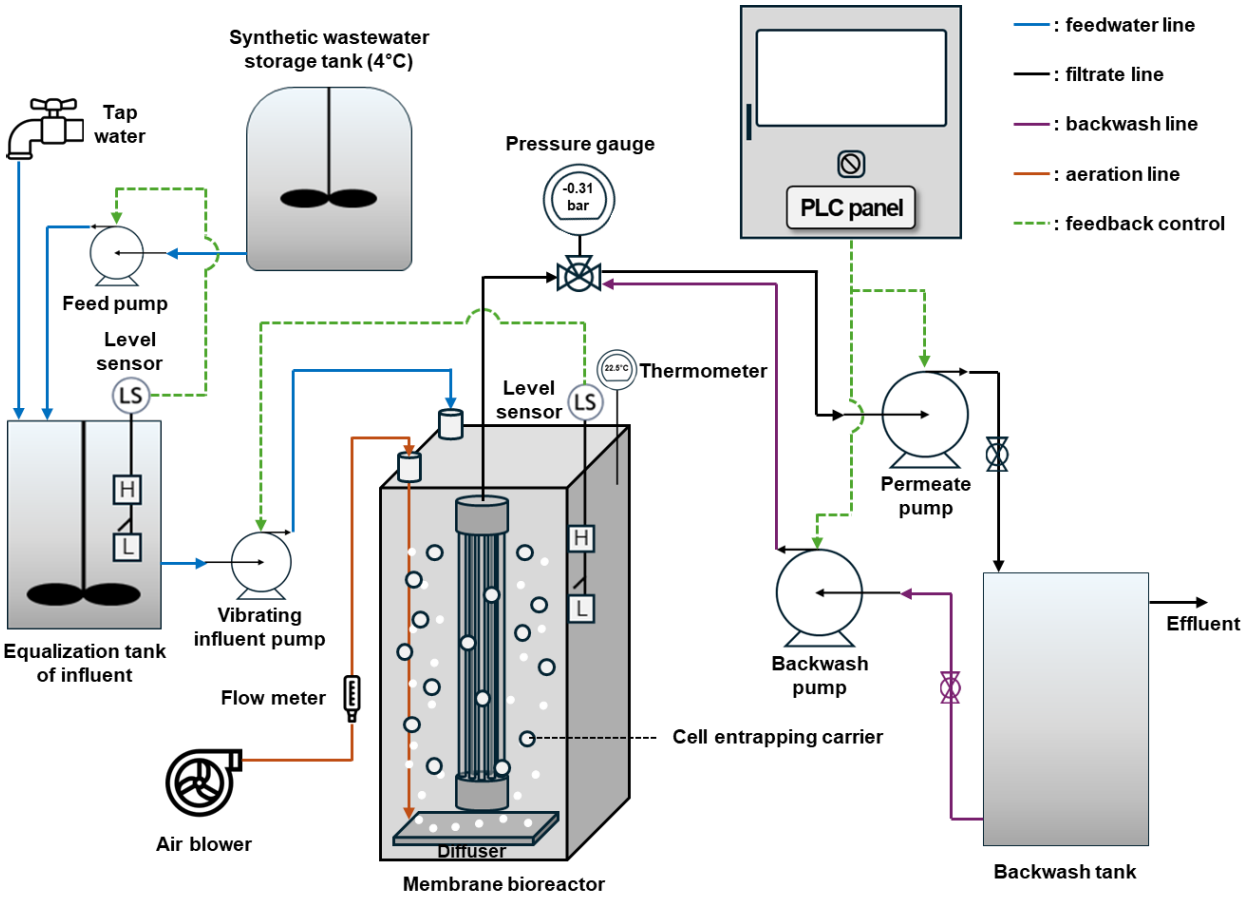


Fig. 3 A schematic diagram of the lab-scale MBR process

monitoring filtration and backwash pump operations, adjusting the inflow rate according to the water level, and conducting real-time data logging. Table 3 presents the specifications and operational parameters of the MBR reactor utilized in the experiment. To validate the fouling inhibition by CEC, the reactor underwent operation under three distinct conditions: cMBR, vMBR, and QMBR. The cMBR was operated under no CEC condition, the vMBR was operated by CEC with no QQ bacteria and QMBR was operated with QQ-CEC. The effective volume of the reactor was 5.4 L, with dimensions set at 15 cm in width, 10 cm in depth, and 40 cm in height. The operational parameters for one cycle included 10 minutes of filtration followed by 1 minute of pause, and the operation stopped upon reaching the permissible pressure of 0.4 bar (Table 3).

The influent utilized in the MBR process experiment consisted of synthetic wastewater formulated according to the influent design specifications of the Seoul T Water Reclamation Center. In Fig. 3, 40-fold concentrated synthetic wastewater was prepared, ensuring that the raw water introduced into the raw water storage tank was diluted in the influent equalization tank using tap water. The concentration of the generated raw water is detailed in Table 4.

2.4 Analytical methods of water quality

The water quality analysis parameters for influent and effluent water from the MBR process include total organic carbon (TOC), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), and total phosphorus (T-P). TOC was measured utilizing a TC-IC TOC analyzer Sievers M9 (Veolia Water Technologies, France), while NH_3-N, NO_3-N, and T-P were assessed using specific analysis kits (Hach, USA) and a spectrophotometer DR 6000 (Hach, USA).

2.5 Evaluation of membrane resistance and EPS, SMP

In order to identify the cause of membrane fouling, physical cleaning was conducted following the attainment of the permissible pressure. The physical cleaning process involved immersing the membrane in a 0.9% NaCl solution, which was subsequently subjected to ultrasonication for 20 minutes at a frequency of 40 kHz using a POWER SONIC 420 sonicator (Hwashin Co., Korea). Following this, chemical cleaning was executed by immersing the membrane in a sodium hypochlorite (NaOCl) solution (1,000 mg/L as Cl_2) and a citric acid solution (5,000 mg/L) for a duration of 24 hours each. Upon completion of each cleaning step, the resistance of the membrane was measured, and the filtration resistance was analyzed in accordance with Eq. (1). Furthermore, the composition of the fouling substances was determined by analyzing the EPS and SMP present in the physical cleaning solution. The physical cleaning solution was centrifuged at 2,688 g for 10 minutes, and the supernatant was filtered through a 0.45 μm pore filter to

Table 3 Operating conditions of the lab-scale MBR

Parameters	Operation values		
Types of MBR	cMBR	vMBR	QMBR
Types of CEC	No	Vacant	QQ
Volume ratio of CEC in reactor (%)	0	1.0	1.0
Reactor volume (L)	5.4		
Aeration rate (L/min)	2.0		
DO in the reactor (mg/L)	2.5 ~ 3.5		
MLSS (mg/L)	6,200 ~ 6,500		
Hydraulic retention time (hrs)	3.5		
Flux (L/m^{2}h)	25		
Filtration cycle	Filtration : 10 min / Pause : 1 min		
Permissible transmembrane pressure (kPa)	40.0		

quantify the SMP. The residual solids were resuspended in a 0.9% NaCl solution, heated in water bath at 80°C for 30minutes, and then centrifuged at 2,688 g for 20 minutes. The supernatant was again filtered through 0.45 μm pores for EPS measurement. The EPS and SMP were analyzed for protein and polysaccharide content, respectively, with the concentrations being summed. Protein concentration was determined using the Lowry method, while polysaccharide concentration was assessed using the phenol-sulfuric acid method (Wei *et al*. 2023, Wang *et al*. 2024)

$$J = \frac{TMP}{\mu(R_m + R_p + R_c + R_{cir})} \quad (1)$$

J = permeate flux (L/m^{2h})

TMP = transmembrane pressure (kPa)

μ = permeate viscosity (Pa-s)

R_m = intrinsic membrane resistance (m^{-1})

R_p = physically reversible fouling resistance (m^{-1})

R_c = chemically reversible fouling resistance (m^{-1})

R_{cir} = chemically irreversible fouling resistance remaining after chemical cleaning (m^{-1})

3. Results and discussions

3.1 Evaluation of CEC physical stability

In accordance with the CEC preparation methods, 20 carriers from Case 1-4 were selected for evaluation of their physical strength through centrifugation (Table 1). Following centrifugation, it was observed that out of the 20 CECs, 6 were damaged in Case 1, 10 in Case 2, and none in Case 3 and Case 4. Furthermore, the stability of expansion in distilled water was assessed. Among 10 mL of CEC, it was noted that carriers in Case 1 and Case 4 were partially dissolved in distilled water, Case 2 was completely dissolved, and Case 3 remained intact without any dissolution. Based on the evaluation outcomes, Case 1 was assigned 50 points, Case 2 received 25 points, Case 3 was awarded 100 points, and Case 4 obtained 75 points (Fig. 4). The optimal concentration of the PVA-SA mixed solution was determined as 8% PVA and 1% SA through the results of the physical strength assessment via centrifugation. Additionally, the evaluation of expansion stability in distilled water revealed that a longer primary cross-linking time led to increased retention of CEC in the reaction tank, indicating poor stability. During the 30-minute double cross-linking reaction between PVA and SA facilitated by Ca2+ ions, the reaction progressed effectively; however, the strength decreased with prolonged exposure to water. Furthermore, previous study reported that prolonged exposure of the carrier to H3BO3 results in an increased rate of microbial mortality. Additionally, it was demonstrated that long-term cross-linking with Na_2SO_4 adversely affects microbial function, attributable to the effects of intracellular osmotic pressure (Takei *et al*. 2011).

Table 4 Synthetic wastewater concentrations

Parameters	Concentration (mg/L)
TOC	94.5 ± 5.1
T-N	40.0 ± 3.8
NH_3-N	38.6 ± 2.2
NO_3-N	1.2 ± 0.9
T-P	4.4 ± 0.7

3.2 Evaluation of MBR process operation performance

Following the physical stability assessment, vacant-CEC and QQ-CEC were produced for incorporation into the continuous operation of the MBR process using the manufacturing procedure outlined in Case #3. Subsequently, the MBR reactor was put into operation. The actual volume of CEC was determined based on the volume ratio of CEC detailed in Table 3, utilizing a measuring cylinder. 1% ratio of carrier volume per reactor volume was introduced to monitor treatment efficacy and transmembrane differential pressure during continuous operation (Fig. 5). The MBR system without CEC required approximately 10 days to reach the permissible pressure limit, while the vMBR system and QMBR system took around 18.8 days and 25.4 days, respectively. The time taken to reach the permissible pressure was comparatively shorter than that of a typical MBR process, likely due to the absence of backwashing conditions during operation.

In the vMBR process, CEC moved within the reactor and collided with the membrane surface, resulting in a scouring effect that mitigated the onset of fouling. This showed a physically mitigation effect on fouling, resulting in a delay of approximately 8.8 days in the increase of TMP. In comparison to the cMBR process, it has been established that in the cMBR system, air bubbles facilitate physical cleaning through aeration. Conversely, in vMBR, CEC and air bubbles concurrently contributes to the mitigation of fouling. Furthermore, QQ-CEC is presumed to

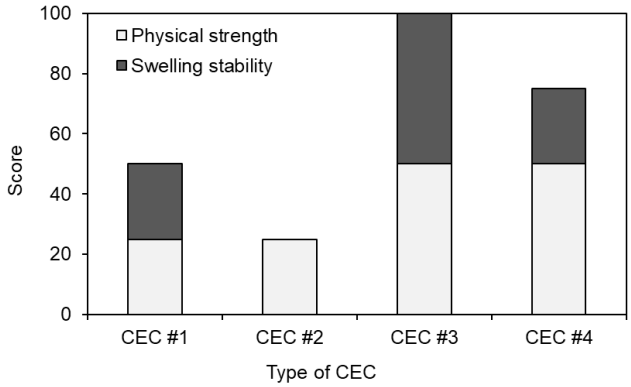


Fig. 4 Physical strength according to CEC manufacturing methods

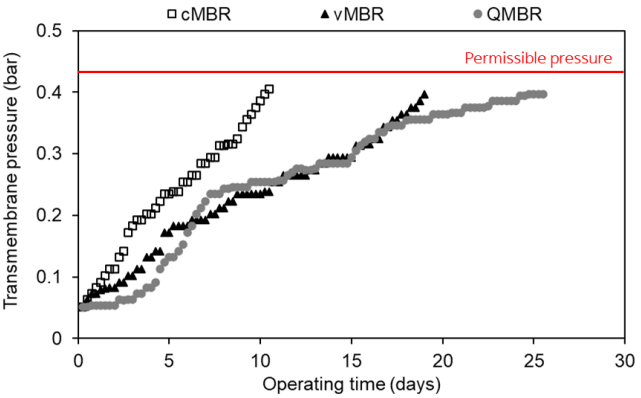
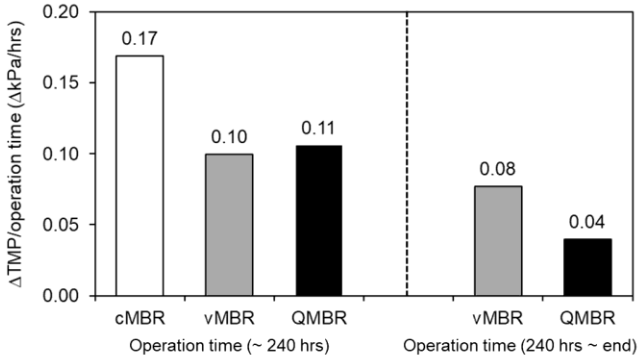


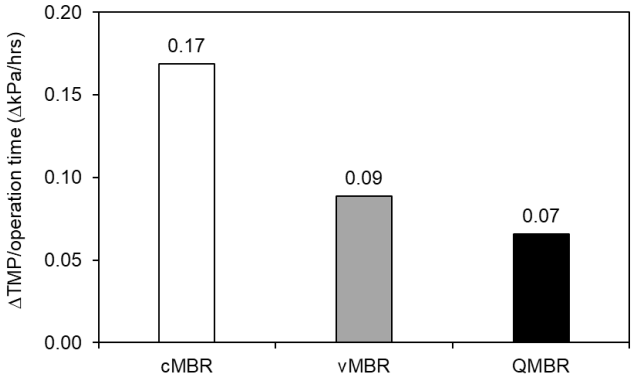
Fig. 5 TMP characteristics under the different conditions of MBR

possess not only a scouring effect but also the ability to postpone biofouling initiation by facilitating the inactivation of AHLs through the QQ mechanism of *BH4* and reducing microbial products and metabolites (Pervez *et al.* 2018). Choi *et al.* (2024) conducted experiments under conditions analogous to those of the present study and reported that it took approximately 3.7 to 9.8 days for TMP to achievepermissible pressure. This finding confirms that the current study demonstrated superior QQ-CEC performance compared to previous research.

To investigate the variation in the rate of increase in TMP over operation time, a comparison was made between the TMP increase rates at 240 hours when the cMBR reached the allowable pressure and the subsequent period (Fig. 6(a)). The analysis revealed that the TMP increase rate during the initial operation up to 240 hours was 0.10 for the vMBR and 0.11 for the QMBR. However, after 240 hours, the TMP increase rate in the vMBR to confirmed 0.08, in contrast to the 0.04 observed in the QMBR. This difference is attributed to the time required for the QQ bacteria to activate and stabilize in the reaction tank. The overall TMP increase rates for the entire operation time were confirmed to be 0.17 in the cMBR, 0.09 in the vMBR, and 0.07 in the QMBR. The stabilization of QQ bacteria in the reactor leads to decrease in the TMP increase rate through the QQ mechanism, indicating its role in delaying to reach permissible pressure.



(a) TMP increase rate by operation time



(b) TMP increase rate by entire operation time

Fig. 6 Analysis TMP increase rate according to operating conditions of MBR

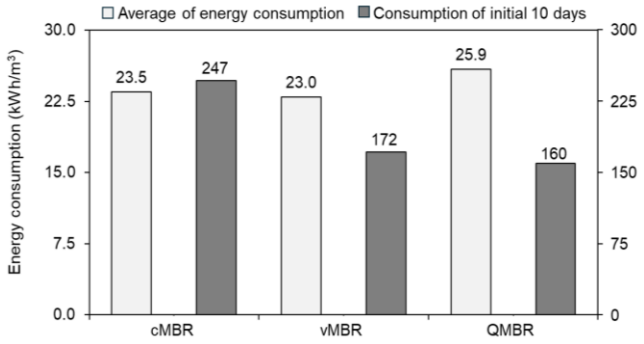


Fig. 7 Analysis of energy consumption according to MBR operating conditions

According to the MBR operating conditions, the filtration energy consumption was analyzed utilizing Eq. (2). The average energy consumption for the entire operating period is illustrated in Fig. 7. It was observed that under the QMBR condition, the average energy consumption was significantly higher than that of other processes, primarily due to the rapid increase in TMP at the onset of operation. However, it can be confirmed in Fig. 7, the energy consumption of QMBR during the initial 10 days was lower than that of the other processes. This observation underscores the substantial influence of the initial increase in TMP on energy consumption. If the TMP is regulated to prevent a rapid increase at the onset of operation, significant reductions in in energy consumption can be achieved.

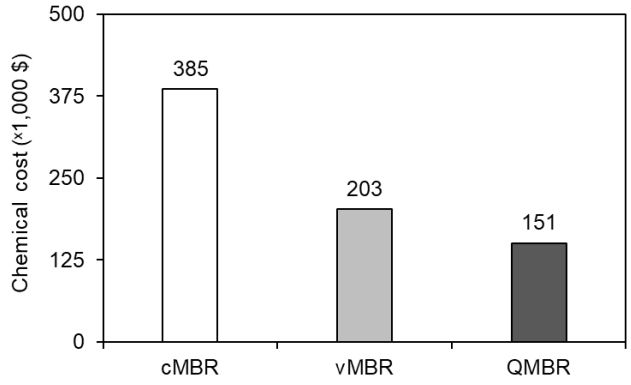


Fig. 8 Analysis of chemical reagent according to MBR operating conditions

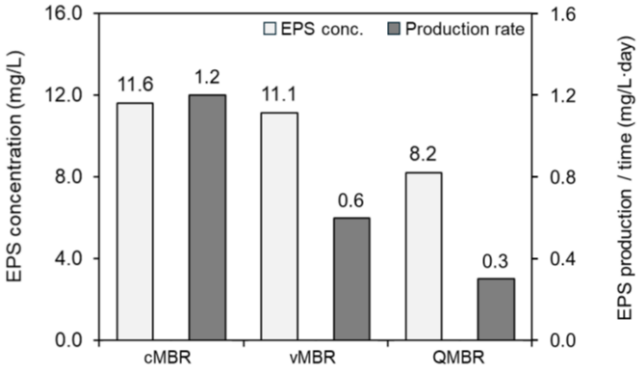


Fig. 9 Analysis of EPS concentrations in physical cleaning wastewater

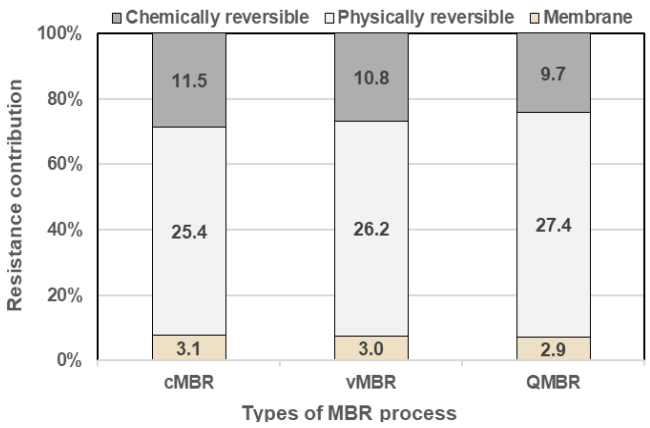


Fig. 10 Comparison of membrane resistance after physical and chemical cleaning

$$E = \frac{1}{\eta t}\int_0^t TMP\ dt \ \ (\text{kWh/m}^3)$$
$$\eta = \text{ energy efficiency (0.6)} \qquad (2)$$
$$t = \text{operating time}$$

Furthermore, the annual consumption costs associated with the 100 m³ MBR process were estimated based on the quantity of chemicals utilized for the chemical cleaning of the membrane, as illustrated in Fig. 8. Under the conditions of the QMBR, biofouling was mitigated, resulting in a reduction of approximately 2.5 times in the duration required for TMP to reach the permissible pressure. Consequently, the frequency of chemical cleaning cycles was decreased, leading to an estimated cost reduction of approximately 39.2%. It is anticipated that the implementation of QQ in a full-scale MBR process will significantly contribute to the reduction of operating costs.

3.3 Evaluation of mitigating biofouling perfomance

After completing the experiment under each condition, the membrane that had reached the permissible pressure underwent physical cleaning. The protein concentration of the physical cleaning solution was then analyzed to quantify EPS. The concentrations of EPS in cMBR and vMBR were determined to be 11.6 mg/L and 11.1 mg/L, respectively, while the concentration of EPS in QMBR was found to be 8.2 mg/L (Fig. 9). It is believed that analyzing EPS during the same operational period under each condition would clearly demonstrate differences in concentration. Furthermore, in cMBR and vMBR, it is inferred that EPS production was not inhibited due to the absence of the QQ mechanism. Conversely, in QMBR, the QQ mechanism of *BH4* reduced EPS production through the QS mechanism of activated sludge microorganisms, leading to the suppression of membrane fouling (Xu *et al*. 2020).

The recovery of the membrane was assessed by TMP following the physical cleaning of the membrane. According to experimental conditions, the initial TMP of the separator was recorded at 3.1kPa, 3.0 kPa and 2.9 kPa. After conducting physical cleaning upon reaching the permissible pressure, the TMP resistance was observed to be 25.5 kPa, 26.2 kPa, and 27.4 kPa. Additionally, after chemical cleaning, the TMP resistance was measured at 11.5 kPa, 10.8 kPa, and 9.7 kPa (Fig. 10). This slight variation is attributed to the lesser amount of chemically reversible fouling caused by EPS called biofilm on the membrane surface in the QMBR.

3.4 Evaluation of removal performance

Table 5 presents the outcomes of the analysis conducted on the water quality concentration of effluent water in each MBR operated under three distinct conditions. The single reactor, operated aerobic, exhibited excellent nitrification rates across all three conditions, and it was confirmed that the denitrification reaction was not induced due to the absence of an anoxic tank. The TOC was consistently eliminated through aerobic oxidation of organic compounds by aerobic heterotrophic microorganisms, demonstrating a high level of stability compared to the standard effluent water quality range of 25 mg/L. However, it was observed that the removal rate of T-P was inadequate as the biological phosphorus removal mechanism could not be initiated due to the absence of anaerobic and anoxic tanks. Although there were slight variations in the treated water concentration among the three conditions, it was determined that the suppression of the QS mechanism by the QQ mechanism did not significantly impact nitrification and organic matter oxidation processes (Iqbal *et al*. 2018, Weerasekara *et al*. 2014, 2016). In prior research, it was

Table 5 Analysis of effluent water qualities

Parameters	cMBR			vMBR			QMBR		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
TOC(mg/L)	3.4	2.6	2.9	3.8	3.3	3.4	4.6	3.4	3.8
NH_3-N(mg/L)	0.4	0.0	0.1	0.4	0.0	0.1	0.4	0.1	0.2
NO_3-N(mg/L)	42.2	38.3	40.4	39.7	36.1	38.8	41.2	38.2	40.2
T-P(mg/L)	4.8	3.5	4.1	4.8	3.8	4.2	5.1	3.8	4.2

observed that the QQ mechanism did not exert a significant influence on alterations within microbial communities, and that these communities exhibited aging over as time passed (Kim *et al*. 2024).

4. Conclusions

This study conducted various experiments to produce CEC using QQ bacteria, *Rhodococcus sp*. *BH4*, to mitigate fouling of MBR. The study confirmed the stable maintenance of CEC in the reactor under specific conditions, involving the mixture of 8% PVA and 1% SA with the first cross-linking process lasting for 30 minutes. As a result of operating MBR, it indicated that the QQ mechanism could delay the time for TMP to reach the allowable pressure by more than 2.5 times compared to the MBR process. Furthermore, it has been established that biofouling can be mitigated through the application of QQ, resulting in a reduction of chemical usage by approximately 39.2%. It is anticipated that employing QQ to address the increase in TMP from the onset of operation will contribute to a decrease in filtration energy consumption. EPS analysis of the physical cleaning solution revealed the lowest concentration in the QMBR, with similar concentrations observed in the cMBR and vMBR. Following operation of the QMBR, the EPS production generated on the membrane surface was found to be 0.32 $mg \cdot L^{-1} \cdot day^{-1}$ that was less than 4 times and 2 times lower compared to the cMBR and vMBR. This suggests that QS inhibition by the QQ mechanism leads to AHLs inactivation and delays fouling of the separator by inhibiting EPS production. The treated water quality did not exhibit significant differences under each MBR condition, indicating that QQ mechanism had no notable impact on pollutant removal. In future research, it is essential to explore phosphate removal methods via CEC surface modification, analyzing AHL signal molecule, optimize treated water quality through the integration of advanced wastewater treatment methods, and investigate the long-term application of the QQ mechanism alongside CEC separation and recovery techniques for scale-up. These approaches should be developed and implemented to enhance the performance of MBR.

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