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Recent advances and future potential of anaerobic ceramic membrane bioreactors for wastewater treatment: A review

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Abstract. Anaerobic membrane bioreactor (AnMBR) treatment has been widely studied in recent years because of the potential for production of bio-energy from wastewater and energy-positive operation of wastewater treatment plants. Several AnMBR systems, including those that incorporate ceramic membranes, take advantage of enhanced water permeability and low membrane fouling potentials. Given that differences in the ceramic membranes may influence the results of AnMBR studies, relevant details are discussed in this review, which focuses on the profiles of common ceramic membranes used in AnMBR, treatment and filtration performances of different anaerobic ceramic membrane bioreactors (AnCMBRs), and the membrane fouling mitigation methods available for effective AnCMBRs operation. The aim of this review is to provide a comprehensive summary of AnCMBR performance, feed wastewater characteristics, operating conditions, and the methods available for effective fouling mitigation.

Keywords: anaerobic ceramic membrane bioreactor; ceramic membrane; feed wastewater characteristics; fouling mitigation method

1. Introduction

Anaerobic processes for treating wastewater are considered more beneficial than aerobic processes in terms of energy recovery. Anaerobic digestion combines organic reduction and energy production, and because no oxygen supply is required, maintenance and operational costs can be reduced (Lin *et al.* 2013). Although anaerobic treatment extracts energy from wastewater, slow growth rates of anaerobic microorganisms, especially during start-up periods, present obstacles to widespread application (Yue *et al.* 2015a).

A membrane bioreactor (MBR) can improve effluent water quality through effective solid-liquid separation and a long solid retention times (SRT) (Garcia *et al.* 2013). Anaerobic membrane bioreactors (AnMBRs) that couple membrane filtration with anaerobic treatment can provide energy-positive wastewater treatment more effectively than other MBRs. Although anaerobic processes have been applied to treatment of high-strength wastewater, interest in treating low-strength wastewater with AnMBRs has increased significantly to compensate for shortcomings in other anaerobic processes by preventing biomass washout (Yue *et al.* 2015a).

However, membrane fouling remains a major obstacle to adoption of AnMBR treatment. Membrane fouling in an AnMBR is considered to be more severe than in an MBR because biomass concentrations in an AnMBR are typically higher (Yue *et al.* 2018). Biogas sparging, re-addition of produced biogas from the bioreactor, is a common fouling mitigation strategy but is not an economical option for AnMBRs because it requires significant energy to recirculate biogas.

Meanwhile, application of alternative membrane materials, including inorganic membranes, offers another option for reducing membrane fouling. Polymeric membranes are most widely used in AnMBR treatment because of cost-effective manufacturing procedures and operational experience (Yue *et al.* 2015a). Ceramic membranes have higher membrane hydrophilicity than that of polymeric membranes, which results in reduced hydrophobic interactions between membrane surfaces and foulants (Jeong *et al.* 2017b). In addition, ceramic membranes have superior chemical, mechanical, and thermal properties, which allow use of more aggressive cleaning agents and lower maintenance costs than those of polymeric membranes (Wang *et al.* 2018, Yue *et al.* 2015a)

This review aims to investigate recent advances in application of ceramic membranes to wastewater treatment through AnMBR systems. Treatment and filtration performances as well as fouling mitigation strategies are systematically investigated in terms of membrane materials and operational conditions. Perspectives from AnCMBR studies are discussed.

2. Influence of ceramic membrane properties on AnCMBR treatment

Table 1 shows the ceramic membranes used in current AnCMBR systems. Most ceramic membranes are composed of alumina (Al_2O_3)-based materials. AnCMBR systems with alumina membranes have been successfully applied to wastewater treatment, achieving acceptable filtration ability, organic removal efficiency, and methane production

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Table 1 Ceramic membrane materials used in recent AnCMBR studies

Ceramic Membrane material	Ceramic Membrane type	Manufacturer	Membrane pore size (μm)	References
	UF		0.08	
Al_2O_3	MF	-	0.2	Yue *et al.* (2015a)
	MF		0.3	
Al_2O_3	UF	ItN Nanovation AG, Germany	0.08	Yue *et al.* (2015b)
Al_2O_3	MF	-	0.5	Aslam *et al.* (2017b)
ZrO_2	UF		100 kDa	
Al_2O_3	UF	Atech Innovations, Germany	0.05	Duppenbecker *et al.* (2017a)
TiO_2	MF		0.4	
ZrO_2	UF	Atech Innovations, Germany	150 kDa	Duppenbecker *et al.* (2017b)
Al_2O_3	MF	Meidensha Corporation, Japan	0.1	Jeong *et al.* (2017a)
pyrophyllite	MF	IB Materials, Co., Ltd., South Korea	0.15	
Al_2O_3	MF	-	0.1	Jeong *et al.* (2017b)
Al_2O_3	UF	ItN Nanovation AG, Germany	0.08	Mei *et al.* (2017)
Al_2O_3	MF	Meidensha Corporation, Japan	0.1	Cho *et al.* (2018)
Al_2O_3	MF	Meidensha Corporation, Japan	0.1	Jeong *et al.* (2018)
Al_2O_3	UF	ItN Nanovation AG, Germany	0.08	Yue *et al.* (2018)
SiC	MF	Cembrane Corporation, Lynge, Denmark	0.1	Cho *et al.* (2019)

(Cho *et al.* 2019), Jeong *et al.* (2018) compared the filtration and treatment performance of polyvinylidene fluoride (PVDF) membranes and alumina-based ceramic membranes. They reported that AnCMBR showed higher chemical oxygen demand (COD) removal and superior filtration performance due to narrow pore sizes and the extremely hydrophilic surfaces of alumina-based ceramic membranes. Recent studies have reported silicon carbide-based membranes as an alternative material because they have a strong negative surface charge at neutral pH values, facilitating reduction in fouling potential. Silicon carbide has the lowest isoelectric point (pH_{iep} = 2.5-3.5) among ceramic membrane materials, such as titania (5.1-6.4), zirconia (6.3-7.1), and alumina (8.0-9.4) (Cho *et al.* 2019). These characteristics of SiC ceramic membranes allow more efficient fouling mitigation than other ceramic membranes as well as increased organic efficiencies (Cho *et al.* 2019).

However, most commercialized ceramic membranes, such as those composed of alumina and silicon carbide, require higher capital costs compared to polymeric membranes. Therefore, developing cost-effective ceramic membranes is a critical issue for practical implementation of AnCMBR systems (Jeong *et al.* 2017a). Several researchers have studied the manufacturing processes of natural-mineral based ceramic membranes, such as dolomite, kaoline, and Moroccan clay (Kumar *et al.* 2015, Zhou *et al.* 2010), as they are expected to involve lower costs. Pyrophyllite ($Al_2Si_4O_{10}(OH_2)$), the other natural-mineral based material, is an environmentally friendly clay that is abundant in the Jeollanam-do Province of South Korea (Ha *et al.* 2016). These membranes have been evaluated and used successfully in AnCMBR systems in terms of treatment efficiency and methane production (Jeong *et al.* 2017a). Alternative development of these low-cost ceramic membranes is warranted.

Membrane pore size is also important for wastewater during AnCMBR treatment. Generally, ceramic membrane filtration can be divided into microfiltration (MF, 0.1-μm pores) and ultrafiltration (UF, 0.01-μm pores). Yue *et al.* (2015a) investigated the effect of pore size on treatment performance in three AnCMBR systems with varying pore sizes (i.e., 0.08, 0.2, and 0.03-μm). Over long periods, pore-blocking was prolonged in membranes with larger pores, resulting in significant reduction in membrane permeability and earlier trans-membrane pressure (TMP) surges. Fouling rates were also higher in membranes with larger pores, although treatment efficiency was not affected because membrane pores with a larger surface area can contain biomass that can cause internal fouling. As smaller pores can maintain higher proportions of colloids and dissolved organic matter (DOM), they are associated with formation of denser cake layers, which are beneficial for membrane filtration because they prevent pore blockage by retaining foulant material. In addition, Yue *et al.* (2015a) observed that protein components increased in permeate with membrane pore sizes, which indicates that proteins of biopolymers can act as main foulants. Proteins (e.g., bovine serum albumin) have spherical shapes that can pass through cake layers and reach membrane surfaces, while polysaccharides (e.g., alginate) have chain structures that hinder passage.

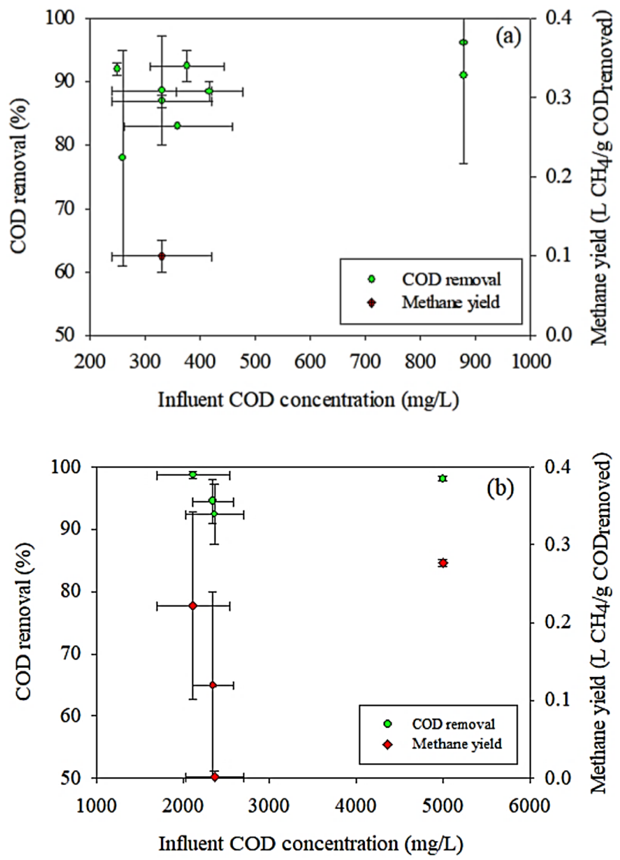

Fig. 1 Treatment performances by influent wastewater concentrations: (a) low-strength domestic wastewater (≤ 1,000 mg/L) and (b) high- strength domestic wastewater (≥ 1,000 mg/L)

Meanwhile, Duppenbecker *et al.* (2017a) evaluated a ZrO_2 UF membrane (molecular weight cut-off =100 kDa), TiO_2 MF membrane (0.4 μm), and Al_2O_3 UF membrane (0.05 μm) in AnCMBR treatment. They reported that the fouling rate was higher with membranes with larger pores, similar to the findings of Yue *et al.* (2015a).

3. Influence of feed wastewater characteristics on AnCMBR performance

COD removal efficiencies of AnCMBR depending on wastewater types and operating conditions are summarized in Table 2. Most AnCMBR studies involved domestic wastewater, and they achieved greater than 80% COD removal efficiency. Aslam *et al.* (2017b) reported a lower COD removal efficiency of 61% under an extremely short HRT and high OLR condition. However, they attributed the low COD removal efficiency to a rate limitation rather than limitations in the ceramic membrane, which is further described in section 4.

Ceramic membranes are appropriate for not only domestic wastewater but also industrial wastewater because of their high stability (Wang *et al.* 2018). Several AnCMBR studies have dealt with industrial wastewater, such as dyeing wastewater and phenol-quinoline-containing wastewater. Zhang *et al.* (2018) compared the performance of an up-flow anaerobic sludge blanket (UASB) reactor with an AnCMBR treating dyeing wastewater. Their results showed that the AnCMBR achieved 20% higher COD removal efficiency than that of UASB. In addition, biogas production was higher in the AnCMBR (0.18 m^3/kg COD) than in the UASB reactor (0.1 m^3/kg COD). They investigated changes in archaeal populations in the sludge, reporting that the AnCMBR had more methane-producing archaea than the UASB reactor, which may cause differences in biogas production. The authors attempted to use an AnCMBR to treat phenol-quinoline containing wastewater, but biodegradability would have been severely affected.

Wang *et al.* (2017) also applied an AnCMBR system to synthetic phenol-quinoline wastewater treatment, achieving excellent organics removal, with a phenol removal rate of 97.6%, a quinoline removal rate of 98.6%, and a COD removal rate of 88.9%. In a recent study, Wang *et al.* (2018) added coagulants such as granular activated carbon (GAC) and polyaluminum chloride (PACl) to an AnCMBR system treating synthetic phenol-quinoline wastewater. They obtained improved treatment performances, with a phenol removal rate of 99.96%, quinoline removal rate of 99.10%, and COD removal rate of 95%. Added GAC removed COD by adsorption and enhanced sludge activity. However, the authors warned about the adverse effect of one-off GAC dosing in terms of fouling. Continuous PACl dosing did not show such adverse effects, but PACl concentrations below 200 mg/L could inhibit quinoline degradation. According to another study (Yu *et al.* 2015), a PACl dose above 500 mg/L was not suggested.

Fig. 1 shows the COD removal efficiencies for treating domestic wastewater treatment under various influent strengths. COD removal efficiencies for high-strength wastewater (≥ 1,000 mg/L) were higher than for low-strength wastewater (≤ 1,000mg/L). A recent study by Jeong *et al.* (2017b) reported that AnCMBRs have been used to co-manage domestic wastewater and food-waste recycling wastewater (FRW) produced from the grinding and dewatering food-waste facilities (Cho *et al.* 2018). They achieved a methane yield of 0.222 ± 0.12 L CH_4/g $COD_{removed}$ and a COD removal rate of 90%. High-strength wastewater helped improve methane production due to the high bio-degradability of organic materials in FRW (Cho *et al.* 2019). For high-strength wastewater, Pang *et al.* (2019) achieved the highest methane yield of 0.277 ± 0.004 L CH_4/g $COD_{removed}$.

4. Influence of operating parameters on AnCMBR performance

Numerous AnCMBR studies have focused on effects of operating parameters on treatment performance. Higher organic loading rates (OLRs) caused by shorter HRTs are generally considered to induce greater carbon conversion from organic compounds to methane gas (Huang *et al.* 2011). Short HRTs and higher OLRs could inhibit treatment performance (Fig. 2 and Fig. 3). For example, Aslam *et al.* (2017b) obsersved methanogenesis rate limitation in an

Table 2 Summary of influent wastewater properties, operational parameters and treatment performances in published AnCMBR studies

Influent type	Average influent concentration (mg COD/L)		Temp. (℃)	HRT (hr)	SRT (days)	OLR (kg COD/m^3·d)	COD removal (%)	CH_4 yield (L CH_4/g $COD_{removed}$)	References
Synthetic DWW		250	25	1.3 – 2.1	N.D.	N.D.	91 - 93	N.D.	Aslam *et al.* (2018)
Synthetic DWW		260	25	0.9 - 3.0	N.D.	2.0 - 6.8	61 - 95	N.D.	Aslam *et al.* (2017b)
Domestic WW		330.4 ± 89.8	25 - 30	7.5	60	N.D.	86 - 88	0.1 ± 0.02*	Yue *et al.* (2015a)
Domestic WW		330.4 ± 89.8	25	7.5	60	N.D.	88.6 ± 8.6	0.1 ± 0.02*	Yue *et al.* (2015b)
Municipal WW	Low strength (≤ 1000 mg/L)	369 ± 98	20	1.7	N.D.	5.8	83	N.D.	Duppenbecker *et al.* (2017a)
Domestic WW		376.2 ± 67.2	N.D.	5	60	N.D.	90 - 95	N.D.	Yue *et al.* (2018)
Domestic WW		417 ± 61	25 - 30	5.8	60	N.D.	87 - 90	N.D.	Mei *et al.* (2017)
Municipal WW		446	20	1.3 – 2.3	N.D.	N.D.	77 - 83	N.D.	Duppenbecker *et al.* (2017b)
Synthetic DWW		878.6	N.D.	18 ± 1.3	∞	1.2 ± 0.03	96.1 ± 5.1	N.D.	Jeong *et al.* (2017a)
Synthetic DWW		878.6	33 ± 2	28	N.D.	0.6	91.0 ± 13.8	N.D.	Jeong *et al.* (2018)
Industrial WW		1500 - 9000	34 ± 1	24	N.D.	1.3 - 1.5	70 - 80	0.18	Zhang *et al.* (2018)
FRW + DWW (diluted FRW)		2115 ± 423	30 - 35	12	∞	2.95 - 3.0	98.7 ± 0.6	0.222 ± 0.12*	Jeong *et al.* (2017b)
FRW + DWW (diluted FRW)	High strength (≥ 1000 mg/L)	2346 ± 237	15 - 35	18 - 22	270	2.17 - 3.12	91 - 98	0 - 0.24*	Cho *et al.* (2018)
FRW + DWW (diluted FRW)		2367 ± 334	35	8.2 ± 0.4	250	5	92.4 ± 4.9	0.002 ± 0.007*	Cho *et al.* (2019)
Synthetic IWW		3490	35 ± 1	48	N.D.	1.75	88.9	N.D.	Wang *et al.* (2017)
Synthetic IWW		3500	35 ± 1	48	N.D.	N.D.	95 -	N.D.	Wang *et al.* (2018)
Synthetic WW		5000	35 ± 2	72	N.D.	1.7	98.1 ± 0.4	0.277 ± 0.004	Pang *et al.* (2019)

COD: Chemical oxygen demand, DWW: Domestic wastewater, FRW: Food-waste recycling wastewater, HRT: Hydraulic retention time, IWW: Industrial wastewater, N.D.: No Data, OLR: Organic loading rate, WW: Wastewater, SRT: Solid retention time.

*These CH_4 yield data were measured at 25°C by modified headspace method (Souza *et al.* 2011).

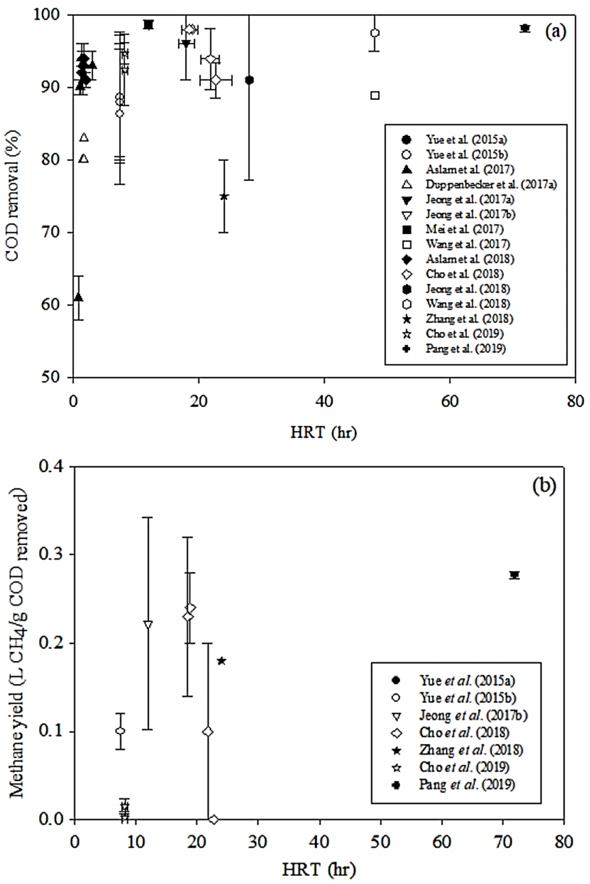

Fig. 2 Influent of HRT on the COD removal and methane production: (a) COD removal and (b) methane production yield

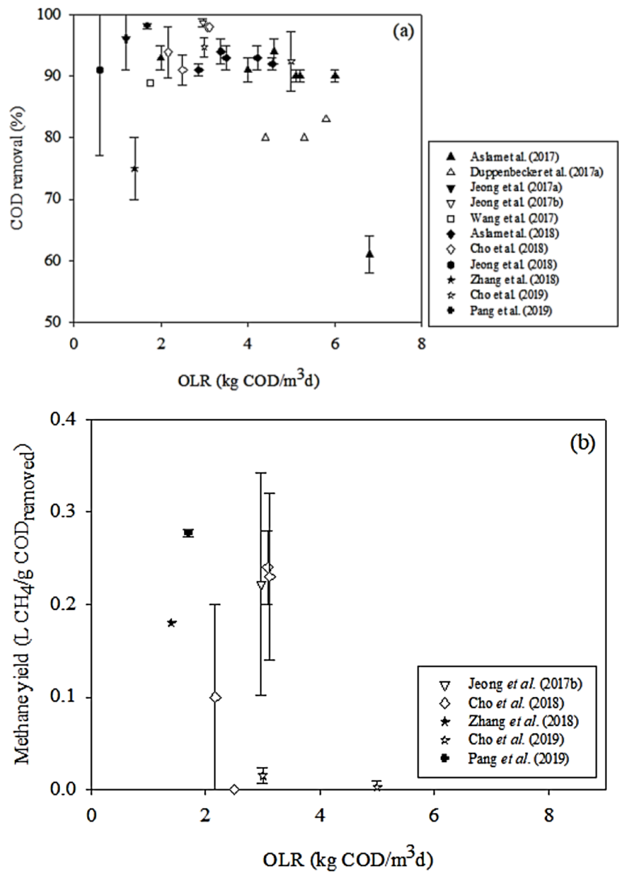

Fig. 3 Influent of OLR on the COD removal and methane production: (a) COD removal and (b) methane production yield

AnCMBR with HRT for 0.88 h and OLR of 6.8 kg COD/m^3·d, achieving poor organic removal of 61%. At a high OLR of 5.8 kg COD/m^3·d, a relatively low COD removal of 83% was achieved (Duppenbecker *et al.* 2017a). This was reported not only for AnCMBR cases, but also reported for aerobic MBR case which demonstrated that increase of HRT positively affected decolorization efficiency (Zonoozi *et al.* 2014).

Temperature is also an important operating parameter because of its effect on microbial activity. In general, anaerobic bioreactors are known to operate efficiently under mesophilic or thermophilic temperature (Gao *et al.* 2014), although aerobic MBR are reported to operate even at 7 °C (Jung *et al.* 2019). Cho *et al.* (2018) decreased the AnCMBR temperature from 35°C to 25°C, 15°C, and 20°C, representing a range of potential seasonal temperatures. The decreased temperature significantly reduced overall COD removal, which is consistent with a previous study (Smith *et al.* 2015). Methanogenic activity depends on temperature as well as OLR, which is implied by cessation of methane production at a psychrophilic temperature of 15°C. By analyzing microbial community structures in a mixed liquor, the authors discovered that major microbial communities in methanogenesis are affected largely by temperature. The relative abundance of hydrogenotrophic methanogens (HMs) such as *Methanomicrobiales* and *Methanobacterials* increased when temperature was reduced from 35°C to 25°C, while that of acetoclastic methanogens (AMs) such as *Methanosarcinales* decreased. This was because hydrogen solubility was improved at lower temperatures, which provided a metabolic advantage to HM over AM. However, these mesophilic HMs lost their biological activity at 15°C, due to an inability to adapt to the lower temperature, which resulted in lack of methanogenesis. Methane yield was recovered slightly when temperature increased to 20°C. Meanwhile, *Methanosaeta concilii* also ceased methanogenesis at 15°C, although it has been reported to act at low temperatures of 10°C. Considering a previous study that reported activity of *Methanosaeta* spp. at 15°C (Smith *et al.* 2013), a sufficient acclimation period could be a solution for recovery of activity of *Methanosaeta* spp.

OLR and temperature are the main factors for enhancing the system performance as they directly affect microbial activity. For low-temperature operation, Cho *et al.* (2018) suggested methanogen inoculation strategies to establish construct psychrotolerant microbial communities. They also suggested an extended acclimation period and a decreased wastewater OLR. As ceramic membranes have high thermal stability, they can operate effectively at thermophilic temperature (> 45°C). The feasibility of thermophilic AnCMBR was presented by Chaikasem *et al.* (2014) who successfully operated two-staged thermophilic AnMBR for synthetic high-strength wastewater treatment at 55°C and

Table 3 Various fouling control strategies employed in AnCMBR studies

Fouling control strategy		MLSS concentration (mg/L)	Flux ($L/m^2 \cdot h$)	TMP increase rate (kPa/d)	References
Physical control	Biogas scouring	12,800-12,900	6	1.19 (80nm) 2.4 (200nm) 3.16 (300nm)	Yue *et al.* (2015a)
	Biogas scouring	10,000	4.5 ± 0.5	N.D.	Jeong *et al.* (2018)
	GAC fluidization	N.D.	17 - 27	N.D.	Aslam *et al.* (2018)
	GAC fluidization	35,770	4.32	N.D.	Wang *et al.* (2018)
	PACl dosing			N.D.	
	Glass beads fluidization	N.D.	7.6	0.014	Duppenbecker *et al.* (2017a)
	PVA-gel beads fluidization	15,400	10	- 0.6	Jeong *et al.* (2017b)
Chemical control	NaOH 1mmol/L + biogas scouring	9,000-13,500	8	2.33	Mei *et al.* (2017)
	NaOH 5mmol/L + biogas scouring			1.3	
	NaOH 10mmol/L + biogas scouring			0.86	
	NaOH 20mmol/L + biogas scouring			0.59	
	NaOH 50mmol/L + biogas scouring			1.03	
	NaClO 0.05 mg/L + biogas scouring	N.D.	10	1.6	Yue *et al.* (2018)
	NaClO 0.25 mg/L + biogas scouring			1	
	NaClO 1mg/L + biogas scouring			0.9	
	NaClO 10 mg/L + biogas scouring			3.3	

MLSS: Mixed Liquor Suspended Solid, N.D.: No Data, TMP: Transmembrane Pressure.

high OLR of 8.2 ± 0.4 kg $COD/m^3 \cdot d$. Yee *et al.* (2019) also operated thermophilic AnMBR for palm oil wastewater treatment at 55℃ and OLR of 2~10 kg $COD/m^3 \cdot d$. Their highest methane yield was 0.56 L CH_4/g $COD_{removed}$. Therefore, further improvements to the thermophilic AnCMBR operation would make it competitive with other AnMBR processes.

Meanwhile, Aslam *et al.* (2017b) commented on the limitation of energy benefits with complex wastewaters compared to synthetic wastewaters. Solutions for improvement of methanogenic activity with more complex substrates are also required. Future research should investigate how these complicated factors influence on the microbial communities in AnCMBR and what more realistic influences on methanogenic activity represent the reactor operations.

5. Ceramic membrane fouling control strategies in AnCMBRs

Table 3 summarizes various fouling control strategies and consequential TMP increase rates in AnCMBR studies. Biogas scouring was the most commonly used method of physical fouling control. However, fluidizing the scouring agent without gas sparging is the most energy-efficient fouling control method (Aslam *et al.* 2017a). Fluidized media that aggressively detach foulants from membrane surfaces are suited for ceramic membranes because of the superior mechanical stability of these membranes (Jeong *et al.* 2017b). Aslam *et al.* (2017b) fluidized GAC particles in an AnCMBR system and remained TMP less than 10 kPa during the first 100 days. However, maintenance cleaning combined with membrane relaxation was necessary for stable long-term operation. They reported the energy produced by methane production was 5.8 times that required for GAC fluidization and permeation pump. Fluidized GAC particles with periodic maintenance cleaning in an AnCMBR achieved a net membrane flux of 22 $L/m^2 \cdot h$ without significant TMP increase (Aslam *et al.* 2018). Wang *et al.* (2018) compared the fouling control effect between GAC fluidizing and PACl dosing and concluded that the latter was more efficient. PACl not only reduced membrane fouling directly, but mitigated fouling indirectly by reducing carbohydrate components through adsorption and increasing the ratio of proteins to carbohydrate (P/C). A high P/C ratio reportedly improves fouling control due to enhanced bioflocculation by the cation bridging effect, resulting in increased porosity and permeability of the cake layer (Arabi and Nakhla 2009).

Duppenbecker *et al.* (2017a) and Duppenbecker *et al.* (2017b) observed the positive effects of fouling control when utilizing fluidized glass beads in AnCMBR treatment. Low crossflow velocities (i.e., 0.073-0.074 m/s) decreased the total required electrical energy for filtration to about 0.31 kWh/m^3 (Duppenbecker *et al.* 2017a). However, the glass beads caused significant damage to the surface of the ceramic membranes. Jeong *et al.* (2017b), which is the only study to achieve a negative value for TMP increase rate, employed PVA-gel bead fluidization as a bio-carrier for fouling mitigation. The negative value indicates that final TMP was lower than initial TMP. PVA-gel beads not only scoured the membrane surface, but provided an alternative surface for microbial growth. This resulted in a reduction in biomass concentration in the mixed liquor, which is the major foulant during AnCMBR treatment.

As a novel approach for fouling mitigation, sludge granulation can potentially be combined with AnCMBR systems. Granular sludge is a sphere-like solid material that forms naturally within fluidized bioreactors. Many studies that incorporated aerobic granular sludge in MBRs have confirmed its effectiveness in reducing fouling (Li *et al.* 2012, Liebana *et al.* 2018, Truong *et al.* 2018). Unlike aerobic granular sludge, anaerobic granular sludge has not been studied extensively in regard to fouling mitigation and therefore requires further examination before it can be substituted for additive forms of scouring media.

Because of the stability and integrity associated with chemical shocks, ceramic membranes would be more suitable than polymeric membranes for chemical membrane cleaning (Yue *et al.* 2018). Chemical enhanced backflush (CEB), which combines conventional physical backflush with chemical cleaning, was applied in two AnCMBR studies (Mei *et al.* 2017, Yue *et al.* 2018). However, CEB methods should be employed with caution because chemical agents can inhibit microbial activity in mixed liquor.

Chemical cleaning by sodium hydroxide (NaOH) had positive effects in in-situ cleaning tests at doses of 10-20 mmol/L, with the lowest fouling rate shown at 20 mmol/L, at which microbial activity peaked (Mei *et al.* 2017). In addition, NaOH doses of 0.05-1.30 mmol/L increased methanogenesis slightly. HMs were notably vulnerable when exposed to high concentrations of NaOH solution. Therefore, 12 mmol/L of NaOH is the most reasonable dose under comprehensive consideration.

Yue *et al.* (2018) employed CEB with a sodium hypochlorite (NaClO) solution in an AnCMBR system. The resulting average fouling rate decreased with NaClO dose below 1 mg NaClO/L reduced the size of the organics in the cake layer or in the membrane pores, dislodging foulants directly from membrane surfaces. In addition, NaClO indirectly mitigated membrane fouling by reducing the accumulation of proteins on membrane surfaces, an effect that was mainly attributed to formation of irreversible fouling that is not easily removed with physical cleaning. An NaClO dose of 1 mg/L was most efficient because extremely high doses (e.g., 10 mg/L) inhibited microbial activities and contributed to fouling problems by stimulating cell lysis.

6. Conclusion

This review paper was prepared to aid AnCMBR implementation by providing a better understanding of existing ceramic membrane properties and their performances, current status, and limitations. Recent AnCMBR studies show a trend toward application of alternative membrane materials to various types of wastewaters. Most AnCMBR studies have reported effective organic removal and methane production at higher flux operations compared to polymeric membrane applications. Ceramic membranes provide useful approaches to mitigating membrane fouling and contribute significantly to reduction of operating and maintenance costs (e.g., chemical cleaning) in practical AnCMBR implications. Further improvements to the proposed strategy of fouling control would have benefits in terms of cost-effectiveness. However, AnCMBR operations remain problematic due to lack of field data for various wastewater streams, and collection of sufficient data over a long period is strongly encouraged to develop a comprehensive understanding of AnCMBRs.

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