Pol. J. Environ. Stud. Vol. 28, No. 5 (2019), 1-18
DOI: *10.15244/pjoes/99303*

Review

Wastewater Treatment by Anaerobic Fluidized Membrane Bioreactor

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Received: 5 September 2018
Accepted: 30 October 2018

Abstract

Anaerobic membrane systems have been frequently applied for the removal of pollutants from wastewater. Membrane fouling is a challenging issue that decreases membrane life-span and increases costs. Anaerobic fluidized membrane bioreactor (AFMBR) is an emerging technology and many studies have shown its outstanding treatment efficiency and fouling mitigation performance. In this paper, wastewater treatment and fouling mitigation performances of AFMBRs are reviewed in detail. Furthermore, different AFMBR configurations and fouling mitigation strategies are discussed. The information presented indicates that the use of fluidized solid materials is improving organic removal efficiency and fouling mitigation. Activated carbon and other solid fluidized particles have revealed promising results, but membrane damage and loss of energy in the form of dissolved methane are particular concerns for sustainable AFMBR operation. However, future studies should focus on the large-scale application of AFMBR with the feed of diverse wastewater and technologies for the recovery of dissolved methane. Finally, this study comprises highly useful data for the researchers who will conduct future AFMBR studies.

Keywords: AFMBR, foulant mitigation, fluidized material, energy

Introduction

Domestic and industrial wastewaters are characterized by high organic content along with other diverse pollutants. Modern wastewater management comprises efficient removal of pollutants and gain energy to fulfil the discharge standards, protect the environment and sustain economic development. Until the last few decades, aerobic treatment technologies were dominant in wastewater treatment. Despite efficient treatment, large energy consumption for aeration, high operational cost and production of a great amount of sludge are the main drawbacks of aerobic systems. Wastewater treatment by anaerobic biological processes has many advantages over aerobic and other removal systems [1]. In addition to higher organic matter removal with less nutrient requirement, lower sludge production and energy-rich methane (CH_4) production are the main outcomes of anaerobic technologies. Various individual and combined anaerobic reactor systems have been successfully applied for the treatment of wastewater [2-5].

Anaerobic bioreactors contain a diverse microbial community, and slow-growing methanogens are very sensitive to changes in environmental conditions. In order to achieve the high treatment performance

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along with energy production, the amount of methanogens and other microbial biomass need to be kept at elevated concentrations. This can be managed by uncoupling the hydraulic retention time (HRT) and sludge retention time (SRT) in anaerobic bioreactors. Anaerobic membrane bioreactors are efficient for retaining a high concentration of biomass and producing high-quality effluent through uncoupling hydraulic and solid retention times [6-8]. This review paper focuses on wastewater treatment by anaerobic fluidized membrane bioreactor (AFMBR). Applications of AFMBR are evaluated based mainly on reactor configuration, treatment performance and fouling mitigation in detail. In addition, microbial community and energy issues are also assessed. Moreover, the summarized information in this paper will be very useful for future AFMBR studies.

Results and Discussion

Anaerobic Membrane Bioreactor

In recent years AnMBRs have received great attention for the treatment of domestic and industrial wastewaters. In addition to high effluent quality, AnMBRs offer less sludge production, easy control and energy production in the form methane [9-11]. Additionally, they are energy-efficient systems and require 70-100% less energy than activated sludge systems [12]. Another advantage of AnMBRs is high biomass retention, operation at relatively short HRT and a smaller footprint [13-14]. Moreover, long SRT enhances the degradation of particulate and colloidal organics, reduces biosolid production and improves effluent water quality [15-16].

Membrane fouling is the major obstacle to widespread application of AnMBR in wastewater treatment since it reduces membrane life-time and increases operational costs [17-18]. Membrane fouling is affected by various parameters including hydrodynamic conditions, material properties, reactor design and sludge characteristics [19-20]. Membrane fouling reduces permeate flux or increases the trans membrane pressure (TMP) depending on the operation mode. In anaerobic membrane systems, biogas sparging is extensively used for fouling control and significant enhancement in operation time, and reductions in sludge cake formation have been reported [21-22]. The main drawback of biogas sparging is its operational cost due to the elevated energy consumption that prevents the widespread application in membrane bioreactors [23-25].

As an alternative to other methods, mechanical scouring of foulants from membrane surface by fluidization of solid particles has gained attention in recent years. It has been proven that solid particles such as activated carbon, mineral oxides, clay minerals, and chitosan, etc., decrease fouling and improve performance in MBRs with low energy consumption [26-29]. Solid particles are also supporting media for the development of microbial communities, and attached-growth biofilms enhance fouling mitigation and organic removal [30-31]. In particular, activated carbon with great surface area has provided remarkable enhancement in fouling control and biomass development. In the study of Ding et al., (2014), they found that GAC addition into the EGSB improved the COD removal efficiency, reduced soluble microbial products, polysaccharides and proteins around 25%, and primarily decreased cake layer resistance by 53.5% [32]. Activated carbon prevents a sudden rise in TMP while amino acids, biopolymers, humics and fulvic acids are effectively removed by both mechanical scouring and adsorption mechanisms [33-34].

Anaerobic Fluidized Membrane Bioreactor

The anaerobic fluidized membrane bioreactor (AFMBR) is a novel emerging technology that combines the properties of anaerobic fluidized bed reactor (AFBR) and submerged membrane filtration. In addition to higher treatment efficiency, long-term operation with no or less membrane fouling could be managed through the fluidization of solid materials [35]. Biodegradation through developed biofilm on fluidization media and the adsorption of pollutants along with membrane filtration provide high-quality effluent [36-37]. Physical interaction of fluidization media with membrane surface removes foulants and improves operational performance. AFMBR technology has advantages of low energy demand and less fouling problems over other AnMBRs [38-39].

AFMBR Configurations

To date, AFMBR studies have been mostly performed as lab-scale and detailed summaries of AFMBR configurations, and performances are given in Tables 1 and 2. AFMBR can be constructed as a single- or two-stage combination with other reactors. In the two-stage system, AFMBR is commonly operated as a post-treatment step for effective removal of pollutants and to meet stringent discharge standards. Single-stage AFMBR studies have been mainly performed to optimize operational conditions, investigate the hydrodynamics of fluidized materials and for model studies [37, 39-42]. Researchers have also conducted comparative studies to evaluate the performance of solid particles and fluidization methods [40, 43]. However, Cheng et al., (2018) constructed a pilot-scale single-stage AFMBR for the treatment of cold-rolling emulsion wastewater from the steel industry [44]. In two-stage systems, AFMBR have been commonly installed for the polishing of effluents from AFBR [36-37, 45-48].

Table 1. Configurations and treatment performance of single-stage AFMBR studies (LS: lab-scale, PS: pilot-scale).

Reactor/ Scale	Study purpose	Membrane characteristic	Fluidized solid material	HRT	Temperature	Feed Wastewater	Pollutant concentration	Operation duration	Study results	Reference
AFMBR/ LS	Examine the effect of different activated carbon	Kubota 0.4 µm	PAC, GAC	3-24 h	35°C,	Synthetic domestic wastewater	460 mg/L	9 days	COD removal >90%, PAC has higher removal performance and fouling mitigation	49
AFMBR/ LS	Comparison of single and two-stage AFMBR	PVDF hollow fiber 0.1 µm	GAC	2.2-3.3 h	25°C	Synthetic wastewater	216 mg/L	195 days	COD removals is independent of HRT	37
AFMBR/ LS	Examination the effect fluidized material on AFMBR performance	PVC flat sheet 0.4 µm	GAC,0.18-2 mm Silica, 1-2 mm PET, 3 mm	-	Ambient temperature	Synthetic wastewater	513 mg	-	All materials are effective on fouling control in different ratios	43
IAFMBR	Examine GAC addition and HRT on wastewater treatment	Hollow fiber 0.4 µm	GAC	4-8 h	35°C	Synthetic and real domestic wastewater	234-425 mg COD/L	160 days	At shorter HRTs, COD removal decreases and TMP rapidly increases	46
IAFMBR/ LS	Examine temperature effect on wastewater treatment	Hollow fiber 0.4 µm	GAC	6 h	35,25,15°C	Synthetic and real domestic wastewater	247-449 mg COD/L	111 days	Decrease in temperature has no significant effect on organic removal until 15 °C	50
AFMBR/ LS	Evaluation of treatment and microbial diversity at different temperature	PVDF/ceramic tubular	GAC	4.2-14 h	25°C,10°C.	Synthetic and real primary effluent wastewater	310-480 mg COD/L	>355 days	Microbial diversity changes with temperature	12
AFMBR / LS	Examine the effect GAC properties on fouling control	PVDF hollow fiber 0.1 µm	Saturated GAC, 0.5-2.0 mm	-	-	Model foulant solution	-	-	Foiling mitigation is affected by GAC size, packing ratio and membrane placing	51
AFMBR/ LS	Effect of acclimation of GAC on treatment	PVDF hollow fiber 0.1 µm	GAC	1.0-1.3 h	22°C	Primary domestic wastewater	92-153 mg COD/L	120 days	Acetate is useful to acclimate GAC	52
AFMBR/ LS	Examine the effect of fluidization methods	PVDF hollow fiber 0.1 µm	GAC	4-8 h	-	Seafood industry	106-408 mg COD/L	230 days	Addition of gas sparging to GAC fluidization increased fouling mitigation	53
AFMBR/ LS	Performance comparison of four bioreactors	PVDF hollow fiber 0.1 µm	GAC	1.3 h	22°C	Domestic wastewater	153-329 260 mg COD/L	131 days	AFMBR effectively remove COD	54
AFMBR /LS	Comparison of fluidization methods	PVDF hollow fiber 0.1 µm	PET, 3mm	-	Room temp.	Model foulant solution	-	25 days	Liquid and gas circulation together increase fouling mitigation by PET	40

Table 1. Continued.

AFMBR/ LS	Investigate treatment performance and fouling mitigation	Al_2O_3 ceramic 0.5 µm	GAC	0.88-3 h	25ºC	Synthetic	260 mg COD/L	395 days	Maintenance cleaning is effective on fouling mitigation	55
AFMBR / LS	Comparison of single and two-stage performance	PVDF hollow fiber 0.1 µm	GAC, 1.0-1.4 mm	3 h	23ºC	Municipal wastewater	100-4590 mg COD/L	260 days	>97% COD and 100% suspended solid removal	56
AFMBR/ LS	Mathematical model presentation to understand fouling	PVDF hollow fiber 0.003 µm 0.1 µm	GAC, 0.18-3 mm	-	-	Synthetic wastewater	178 mg COD/L	-	Large GAC is more efficient on fouling mitigation	41
AFMR/LS	Comparison of coated and uncoated ceramic membrane for treatment and fouling mitigation	Flat-tube ceramic membranes, 1 µm, 0.1 µm	GAC	-	-	Synthetic industrial wastewater	662 mg TOC/L	-	For both membranes COD removal was higher than 90%	57
AFMBR/ PS	Investigate COD removal and microbial diversity	PVDF hollow fiber 0.035 µm	GAC, 0.6-2.0	1.5-4.0 d		Cold-rolling wastewater	860-1240 mg COD/L	302 days	73-98% COD removal	44
AFMBR/ LS	Model development	PVDF hollow fiber 0.1 µm	PET, 3.0 mm, Silica 1.5 mm	1.6-1.8	-	Synthetic wastewater treatment	260 mg COD/L	-	PET was better on fouling mitigation and model had higher fit to experimental data	42
AFMBR/ LS	Model development	Flat-tubular ceramic membrane, 0.5 µm	PET-3.0 mm	2.88-7.5 h	25ºC	Synthetic wastewater treatment	250 mg COD/L	250 days	Developed model combining biological anaerobic model and fouling model fitted well to experimental data	58

Table 2. Configurations and treatment performance of two-stage AFMBR studies (LS: lab-scale, PS: pilot-scale).

Reactor/Scale	Study purpose	Membrane characteristic	Fluidized solid material	HRT	Temperature	Feed Wastewater	Pollutant concentration	Operation duration	Study results	Reference
AFBR+AFMBR/ LS	Wastewater treatment	PVDF hollow fiber 0.1 µm	GAC	2.0-2.8+2.2 h	35ºC	Synthetic domestic wastewater	513 mg COD/L	120 days	99% overall COD removal. 0.028kWh/m3 energy production by AFMBR	36
AFBR+AFMBR / LS	Treatment of domestic wastewater	PVC hallow fiber MF 0.1 µm	GAC	(0.75-1.5 h)+(1.0-1.9 h)	25ºC	Primary domestic wastewater	153 mgCOD/L	192 days	Two-stage is efficient on treatment and less energy demand	59

Table 2. Continued.

AFBR+AFMBR	Treatment of wastewater	PVDF hallow fiber	GAC	1.0 h+1.3 h	25ºC	Primary domestic wastewater	154-235 mg COD/L	310 days	84-91 COD% removal and low energy consumption	60
AFBR+AFMBR	Examine effect of temperature on treatment performance	PVC hallow fiber MF 0.1 µm	GAC	1h+1,3 h	10-25ºC	Primary domestic wastewater	235-300 mg COD/L	14 months	Low temperatures have no noticeable negative effect on organic removal	61
AFBR+AFMBR/ LS	Comparison of single and two-stage AFMBR	PVDF hollow fiber 0.1 µm	GAC	0.8-1.5 h	25ºC	Synthetic wastewater	216 mg COD/L	202 days	Single and two-stage systems had similar removal performance	37
AFBR+AFMBR/PS	Continuous treatment of domestic wastewater	PVDF hollow fiber 0.03 µm	GAC	2.0-11.1+2.6-4.8	8-30ºC	Primary domestic wastewater	273-362 mg COD/L	485 days	81-94% COD removal	45
MFC+AFMBR/LS	Domestic wastewater treatment by two-staged AFMBR	PVDF hollow fiber 0.1 µm	GAC	4-24 h+ 1 h	25ºC	Primary domestic wastewater	210 mg COD/L	50 days	Effective and energy-efficient wastewater treatment performance	62
AFBR+AFMBR/ LS	Removal of pharmaceuticals and organic matter from municipal	PVDF hollow fiber < 0.1 µm	GAC	0.45-8.0 h+0.83-3.0 h	20-25ºC	Primary municipal wastewater	38-1000 mg COD/L	299 days	>90% pharmaceuticals removal	63
ABR+AFMBR / LS	Wastewater treatment	PVDF hollow fiber 0.1 µm	GAC	3 h+(0.93-1.16) h	25ºC	Synthetic wastewater	250 mg/L	200 days	AFMBR has high polishing potential	64
AFBR+AFMBR / PS	Evaluation of membrane integrity	PVDF hollow fiber 0.03 µm	GAC 0.80-4.0 mm	-	-	Primary domestic wastewater	-	765 days	Membrane damaged significiantly	65
DFF+AFMBR/LS	Waste treatment and fouling mitigation	PVDF/ceramic tubular	GAC	4.2-8 h+1.8-6h	25ºC,10ºC.	Synthetic and real primary effluent wastewater	310-480 mg COD/L	365 days	>94% organic removal, and efficient fouling mitigation	48
MFC+AFMBR/	Wastewater treatment by two-staged system	PVDF hollow fiber 0.1 µm	GAC	8.8+1.4-3.8 h	Room temperature	Primary domestic wastewater	316-469 mg COD/L	112 days		66
IAFMBR (AFBR+AFMBR)	Treatment of benzothiazole wastewater	Hollow fiber 0.4 µm	GAC	4-8 h	35ºC	Synthetic benzothiazole wastewater	3000 mg COD/L	185 days	96% benzothiazole removal	67

Table 2. Continued.

AFBR+AFMBR / PS	Comparison of single and two-stage performance	PVDF hollow fiber 0.1 µm	GAC 1.0-1.4 mm	2 h+2h	23°C	Municipal wastewater	To second AFMBR 36-3060 mg COD/L	260 days	>97% COD and 100% suspended solid removal. AFBR is unnecessary	56
AFBR+AFMBR	Wastewater treatment	Ceramic UF100 and MF0.4	Glass beads, 1.5 mm	1.6-1.8 h	20°C	Municipal wastewater	369 COD mg/L.	47 days	80-83% COD	47
AFBR+AFMBR	Wastewater treatment	Ceramic UF100	Glass beads, 0.8-1.2, 1.5 mm	1.3-2.3 h	20°C	Municipal wastewater	446 COD mg/L.	154 days	77-83% COD removal, larger glass beads provided better fouling mitigation	68
IAFMBR (AFBR+AFMBR)/ LS	Effect of HRT on benzothiazole removal and microbial community	PVDF hollow fiber 0.4 µm	12-24 h	12-24 h	35°C	Synthetic Benzothiazole wastewater benzothiazole	2961-3337	297 days	COD removal >90%, microbial diversity is affected by HRT	69
AFBR+AFMBR	Wastewater treatment and fouling mitigation	Double sided flat-tubular ceramic membrane, 0.5 µm	GAC	1.3-2.1 h	25°C	Synthetic domestic	250 mg COD/L	350 days	93% COD removal with high energy-efficient operation	70

An integrated anaerobic fluidized bed membrane bioreactor (IAFMBR) was constructed by combining the properties of AFBR and AFMBR in the same reactor. IAFMBR consists of outer, middle and inner tubes and the outer tube is operated as AFBR and its effluent is fed to AFMBR in an inner tube [46, 50, 67, 69]. Some researchers have installed AFMBR as a polishing treatment for the effluent from different reactors. Experimental results have proven that AFMBR is a very successful polishing reactor for the removal of remaining pollutants from down-flow floating media filter (DFM) [48], anaerobic baffled reactor (ABR) [64], upflow sludge blanket reactor (UASB) [53] and microbial fuel cell (MFC) [66, 62]. Bae et al., (2014) compared the performances of single-stage and two-stage AFMBRs for the treatment of municipal wastewater [37]. In both systems, AFMBR achieved considerable COD (97%) and suspended solid (100%) removal efficiencies. Researchers concluded that AFMBR alone provides superior effluent quality, and eliminating first-stage AFBR has no significant effect on overall treatment performance. Similar outstanding performance of single AFMBR were reported for the treatment of low-strength synthetic wastewater for more than 200 days continuous operation. Besides, single AFMBR offers benefits of less energy consumption and lower construction and operational costs. However, raw wastewater characteristics, desired effluent quality, characteristics of membrane and fluidizing solid materials should be considered for performance comparison and system design.

Membrane is a crucial component of AFMBR and different membrane types and modules have been experienced for wastewater treatment. Among polymeric membranes, PVDF hollow fiber and flat-sheet membranes with different nominal sizes have been configured into AFMBRs [39-41, 60-62, 65, 71]. According to test results, long-term integrity of PVDF hollow-fiber membranes manufactured with the same materials and processes vary considerably between manufacturers [72]. On the other hand, PVC hollow-fiber and flat-sheet membranes have been preferred due to their low costs and high mechanical strength [43]. In recent years, the use of ceramic membranes in AFMBR operations has gained much interest due to higher resistance against harsh environmental conditions [42, 47, 55]. Düppenbecker et al. (2017) stated that higher burning temperature during the manufacture of ceramic membrane provides higher resistance against mechanical scouring [68]. Ceramic membranes can be used with or without coating materials in MBR applications. Ahmad et al. (2018) compared the performances of uncoated and coated flat-tubular ceramic membranes consisting of 80% pyrophyllite and 20% of alumina with nominal pore of 1.0 µm [57]. They found that coated membrane had higher organic removal efficiency and achieved higher fouling mitigation performance when GAC particles were fluidized.

Various fluidizing solid materials, namely activated carbon [36, 44, 52, 66], glass beads [68], silica [43], and polyethylene terephthalate (PET), have been used in AFMBR reactors. Granulated active carbon (GAC) and powdered activated carbon (PAC) have been mostly utilized due to higher mechanical scouring efficiency and pollutant removal capacity. GAC also has the advantage of biofilm development on a surface that contributes improvement on biological treatment performance of AFMBR. Additionally, biofilm on GAC enhances fouling mitigation efficiency by lowering VSS in bulk liquid and decreasing microbial extracellular polymeric substances (EPS) and soluble microbial products (SMP) [37, 40]. COD removal performance of microbial biofilms is quite high, even in harsh conditions and is not significantly affected by the changes in operational parameters [45]. Fresh GAC [50, 57, 60-62, 65] is widely used in AFMBR operations and some researchers also have used saturated [51] and biologically active carbons [44, 55]. Among them, fresh GAC particles have been proven to have more efficient fouling mitigation and critical flux improvement [57]. Moreover, diffuser, nozzle or cobblestones can be placed at the bottom of the AFMBR for supporting the fluidized media and uniform distribution of recirculation wastewater [43-44, 57-58]. Düppenbecker et al., (2017) fixed a wire cloth at the bottom of the membrane module for the same purposes, but frequent clogging by biomass dropped pressure and increased energy consumption [47].

Treatment of Organic Matters

AFMBR studies have been performed mainly for the removal of organic matters by feeding real or synthetic wastewater. To date, most of the studies were conducted by feeding low-strength wastewater. Domestic wastewater has been mainly used as feedstock, whereas few studies were performed with industrial wastewater. Dutta et al. (2014) examined the removal of pharmaceuticals and organic matters from municipal wastewater by a two-stage AFMBR [63]. A pilot-scale single-state AFMBR was applied for polishing the treated cold-rolling emulsion wastewater from the steel industry with COD range of 860-1240 mg/L. Single AFMBR was operated for the treatment of effluents of synthetic textile and seafood industry wastewaters from UASB and AFBR, respectively [53, 57]. Integrated anaerobic fluidized-bed membrane bioreactors (IAFMBR) were successfully operated for the treatment of high-strength synthetic benzothiazole production wastewater [69]. Domestic and industrial wastewaters are rich in organic matter and also contain nitrogen and phosphorus in various forms. Chaiprapat et al., (2016) reported that approximately one third of the nitrogen in the digestate of UASB treating seafood processing wastewater was organic nitrogen [53].

Real wastewater may contain coarse materials and it is better to feed them after pre-treatment or settlement to AFMBR. Many researchers preferred primary clarified domestic wastewater in their AFMBR studies [41, 61-62]. Düppenbecker and his colleagues applied 160 µm pre-screening on municipal wastewaters [47, 68]. Dutta et al. (2014) applied pre-treatment using a 10 µm filter for sieving domestic wastewater, while Bae et al. (2013) compared the effect of pre-treatments of 10 µm cartridge filter and 1 mm screen for the treatment of primary settled domestic wastewater in two-stage AFMBR [63, 60]. Pre-treatment with 10 µm provided 60% TSS removal, but 1 mm screening has insignificant efficiency. Although influent COD concentrations after two pre-treatments were different, AFMBR supplied similar effluent quality [60]. Furthermore, variations in pollutant concentrations of influent of real wastewater should be considered during the AFMBR operation. Especially TSS and COD fluctuations may induce big load changes on a bioreactor and accelerate membrane fouling.

Working with synthetic wastewater is useful for investigating the parameter in detail and excluding undesirable factors. Hu and Stuckey (2007) used synthetic wastewater (460 mg COD/L) [49]. In some operations, AFMBR was fed by a low-strength synthetic wastewater containing a mixture of sodium acetate and propionate with a total COD concentration of 250 mg/L [55, 58, 70]. AFMBR can be operated first with synthetic wastewater until it obtains stable performance, and then real wastewater is fed to the reactor. Seib et al., (2016) fed the reactor by synthetic primary effluent wastewater for 320 days and then continued with primary effluent wastewater [48]. Gao and his colleagues first fed the integrated anaerobic fluidized bed membrane bioreactor (IAFMBR) with synthetic wastewater containing acetate as a substrate and then gradually fed it with domestic wastewater [46, 50]. Researchers have also preferred model foulant solutions to investigate the effects of conditions on fouling mitigation and hydrodynamics of fluidized solid particles in the reactor. In a model solution, bovine serum albumin and sodium alginate are used to represent proteins and polysaccharides, whereas polystyrene and bentonite are particulate foulants [39-40, 67, 73].

Pollutant-removing mechanisms in AFMBR are mainly membrane filtration and biodegradation, while adsorption makes for a great contribution in the case of GAC fluidization. In two-stage systems, AFMBR is mostly applied post-treatment for polishing remaining pollutants. Even treatment efficiency of the first step of a two-staged system is weak, with efficient removal mechanisms in AFMBR ensuring high effluent quality. Bae et al., (2014) compared the performances of single and two-stage AFMBRs for the treatment of low-strength synthetic wastewater (200 mg COD/L) at 25ºC. They found that a two-stage AFMBR system is capable of removing most biodegradable organics at relatively short HRT [37]. Kim et al., (2011) reported that AFMBR provided additional 87% COD removal after AFBR, and total removal efficiency was 99% in a two-staged system

[36]. In another study, overall removal efficiencies in two-stage increased to 96% COD and 100% TSS with superior polishing performance of AFMBR [64].

A two-stage AFMBR system was found to be very efficient for the removal of pharmaceuticals and organic matter from municipal wastewater. With effective membrane filtration, individual treatment performance of AFMBR was higher than AFBR, and 97% of target pharmaceuticals were removed in a two-stage system [63]. The combination of MFC and AFMBR is a promising treatment system to be used in the future with their superior treatment performance of domestic wastewater at ambient temperature. Almost half of the soluble COD was consumed by microorganisms in MFC, and total COD removal efficiency of MFC+AFMBR was 92.5%. The combination of settling in MFC and membrane filtration in AFMBR achieved 99% TSS removal [62]. Outstanding treatment performance of MFC and AFMBR is compatible with other two-staged systems applying for the treatment of domestic wastewater [47, 63]. Similar to the AFMBR system, IAFMBR also has higher tolerance against variations in influent pollutant load and achieved elevated organic removal efficiencies. IAFMBR produced stable COD removal performance (93.6-95.6%), and even AFBR removal efficiencies fluctuated at different influent benzothiazole [47].

Treatment performance of AFMBR is affected by membrane properties, HRT, temperature and organic loading. Membrane characteristics may act in different roles on the removal of pollutants. Düppenbecker et al. (2017) reported that overall COD removal was between 80% and 83% in all membrane types, although removal of dissolved COD with UF membranes was between 50% and 55% and MF with 41% [47]. AFMBR was operated using uncoated and coated ceramic membranes without GAC fluidization for the treatment of synthetic textile wastewater [57]. Coating with alumina decreased the pore size of ceramic membrane and increased organic rejection efficiencies from 60% to 71%. When AFMBR was operated with GAC fluidization, organic removal efficiencies of both membranes were higher than 90%. In addition, developing the foulant layer on membrane surface may act as a secondary membrane layer and improve rejection performance. Hu and Stuckey (2007) found that concentrations of COD and total VFAs in the reactor increased 3.3 and 5 times due to the rejection of organics by the cake layer on the membrane [49]. Enhancement in organic removal capacity positively affects methane production in AFMBR. Use of membrane in the anaerobic fluidized reactor induced a 30% increment in methane production, while specific methane production values were 0.28, 0.29 and 0.32 mg CH_4/mgCOD with MF, UF100 and UF005 membranes, respectively [47, 68]. Li et al. (2017) examined the effect of increased benzothiazole on IAFMBR performance and found that biogas production steadily decreased with the increase in benzothiazole concentration, but methane yield was stable at around 0.31 $m^3CH_4/kgCOD_{removed}$ [67]. Interesting results were reported by LaBarge et al. (2016) for the treatment of domestic wastewater at ambient temperature [52]. Researchers applied four different acclimation methods on GAC and found that the acclimation of GAC communities to acetate substrate considerably enhance organic removal performance. Experimental results indicated that AFMBR performance can be improved by the acclimation of GAC before the operation and they achieved a COD increase from 63% to 84% after acetate acclimation.

Unlike other biological systems, AFMBR generally provides high organic removal performance at relatively short operational HRTs. In a two-stage system, AFMBR is very prospering for polishing the remaining VFAS from the effluent of the first reactor. Hu and Stuckey, (2007) operated a mesophilic AFMBR at HRT of 3 h for the treatment of synthetic wastewater (460 mg COD/L) and 95% of COD was removed [49]. Besides, complete VFA degradation and 75-80% soluble COD removal was obtained by two-staged AFMBR at HRT of 1.32 h at 25ºC [70]. In anaerobic treatment systems, lowering HRT increases organic loading on biomass and this may cause VFA accumulation and a reduction in reactor performance. Gao et al., (2014) investigated the impact of steady HRT reduction on the performance of an AFBR+AFMBR system [46]. In a two-stage system COD removal was the highest, with 76% at HRT of 8 h and then declined to 54.1% at HRT of 4 h. At the same time, volumetric COD removal was 0.69 g COD/L at HRT of 8 h and it increased to 0.95 g COD/L day at HRT of 6 h and did not change at HRT of 4 h. Researchers also reported an increase in methane production with the decrease in HRT. Similarly, Charfi et al., (2018) found that COD removal performance decreased at higher HRTs, but VSS is completely removed by the microfiltration membrane in all conditions [42]. However, Chaiprapat et al. (2016) obtained a slight increase in COD removal with the decline in HRT due to the increase in biomass within the reactor [53]. In contrast, some researchers observed no correlation between HRT increment and COD removal from wastewater [37, 45]. Similary, Kim et al. (2016) operated the AFMBR post-treatment for MFC effluent at different HRTs [66]. AFMBR produced similar COD removal efficiencies at all HRTs tested, which shows that AFMBR performs well at short HRT, and increasing HRT over 3.8 h has no noticable effect. Overall COD removal of MFC+AFMBR was 76% and both reactors contributed similar organic removal performance. Yoo et al. (2012) the average effluent chemical oxygen demand and biochemical oxygen demand concentrations of 25 and 7 mg/L yielded corresponding removals of 84% and 92%, respectively. Also, near complete removal of suspended solids was obtained. Biosolids production, representing 5% of the COD removed, equaled 0.049 g VSS/g BOD(5 reported that the reduction in HRT did not affect the performances of AFMBR alone and in the two-staged system, while average COD removal efficiencies were 65% and 84%, respectively [59]. However, TSS removal in both systems slightly declined at lower HRT. Unlike to above-mentioned short HRT values, high-strength wastewaters need longer HRT values for effective treatment. Cheng et al., (2018) fed the AFMBR with high-strength real industrial wastewater (860-1120 mg COD/L) and obtained 90% organic removal at HRT of 1.5 days [44]. IAFMBR was operated at HRT range of 12-24 h for the treatment of benzothiazole wastewater at 35ºC. COD removal efficiencies were stable and slightly reduced from 93.6% at HRT of 24 h to 90.9% at HRT of 12 h.

Temperature is a critical factor on microbial activity, hydrolysis and pollutant removal performance. At lower temperatures a reduction in microbial activities and lower hydrolysis of organics are the main drawbacks of anaerobic treatment. AFMBR studies have been mostly performed at ambient temperatures [52, 58, 62, 70] or psychrophilic conditions [12, 50, 61] while fewer reactors were operated at mesophilic temperatures [46, 50, 69]. Comparative studies have been conducted to monitor the effect of changes in temperature on AFMBR performance. Shin et al. (2014) operated a pilot-scale two-stage AFMBR at actual daily temperatures between 8ºC and 30ºC in order to observe seasonal change [45]. Gao et al. (2014) operated IAFMBR by steadily decreasing temperature from mesophilic (35ºC) to psychrophilic (15ºC) conditions [50]. Seib et al. (2016) indicated that BOD_5 reduction efficiency slightly decreased from 96% at 25ºC to 94% at 10ºC during the treatment of municipal primary effluent [48]. Accordingly, Shin et al. (2014) indicated that treatment performance of two-staged AFMBR was dramatically affected with the changes in seasonal temperatures [45]. Average COD removal was 81% in winter, which increased to 89% and 94% in spring and summer periods, correspondingly. Even biological activity is affected at lower temperatures, with higher sorption capacity of GAC compensating the difference and removal efficiency of COD, which was always retained over 80%. Gao et al. (2014) found that organic removal was the highest at mesophilic conditions (35ºC). Decreasing the temperature to ambient values (25ºC) had no crucial effect on COD removal [50]. However, removal efficiency and volumetric removal rate of COD sharply dropped from 67% and 0.81 gCOD/L to 51% and 0.73 g COD/L after temperature was reduced to 15ºC. This drastic decrease in organic removal was likely related to the reduction in slow microbial activity along with higher volumetric COD loading. Similar trends were observed in methane production. Methane yields were 0.19 CH4 $L/gCOD_{removed}$ at 35ºC and 25ºC, but it rapidly decreased to 0.14 CH4 $L/gCOD_{removed}$ at 15ºC. Inversely, Yoo et al. (2014) obtained no significant decrease when temperature of AFBR+AFMBR was decreased from 25ºC to 10ºC for the treatment of domestic wastewater. Overall, COD and BOD_5 removal efficiencies were over 89% and 94% in all conditions. COD was removed mainly by AFBR in all cases and the contribution of AFMBR on overall organic removal increased with the decrease in temperature because of higher sorption capacity of GAC and membrane filtration together [61].

The presence of VFA in effluent of anaerobic reactors indicates the incomplete conversion of organics to methane. Dominant organic acids are acetic, propionic, valeric and butyric acids in anaerobic systems. Biofilm on GAC are very active on VFA consumption and effluents of AFMBR systems contain fewer VFAs than gas-sparging anaerobic MBRs [55]. In anaerobic reactors, VFA production is very sensitive to the changes in operational conditions. Acetate concentration sharply increased about three times when HRT was reduced from 24 h to 12 for the treatment of benzothiazole, while acetate to total VFA ratio was the lowest at the highest HRR. Temperature has a similar effect to HRT on VFA generation. Gao et al. (2014) observed changes in COD removal mechanisms with the increase in VFA accumulation at lower temperatures [50]. At 35ºC, more than half of organics were converted methane, but that decreased below 40% at 15ºC. However, the COD:VFA ratio increased almost twofold. Three-fold higher acetate was detected at 15ºC than 35ºC in both reactors of two-stage AFMBR. The percentage of acetic acid increased from around 50% to over 70%, with the decrease in temperature from 35ºC to 15ºC. These significant changes in VFAs and acetic acid amounts are related to the reduction in methanogenic activity. On the contrary, dropping a temperature from 15ºC to 10ºC did not cause any change in VFA concentration because of reduced hydrolysis [61]. In the operation of IAFMBR, VFA accumulation was observed with the increase of influent COD, and 36.1% of effluent COD was comprised of organic acids while the remainder was SMP.

Removal of Nutrients

Generally speaking, anaerobic microorganisms have lower nitrogen and phosphorus removal capacities. In AMFBR systems, nitrogen can be removed through biomass synthesis, adsorption to GAC and particulate settlement. Chaiprapat et al. (2016) reported that 18-35% of ammonia nitrogen from seafood-processing wastewater was removed in an AFMBR system [53]. Researchers found that biogas comprised 30-43% of nitrogen gas that originated from denitrification of nitrogen in AFMBR. The source of nitrate was aeration during storage in the feeding tank. In another study, nitrogen content was found in the range of 37-50% in biogas, and this was associated with the stripping of nitrogen gas in primary wastewater influent [59]. Yoo et al. (2014) concluded that the release of stripped nitrogen in biogas decreased from 61% to 34% in AFMBR with the decrease in temperature, which was due to the significant increase in influent BOD5 load of AMFBR from AFBR effluent [61]. Shin et al. (2014) indicated that total phosphorous and nitrogen did not change significantly during pilot-scale treatment of domestic wastewater at different temperatures and HRTs [45].

The presence of sulfate in influent wastewater negatively affects organic removal performance of anaerobic bioreactors. Sulfate is reduced to sulfide with the use of some organic carbon, and sulfate-reducing bacteria competes with methane-producers [45, 47]. Sulfide in biogas is toxic to living organisms and corrosive to metals, and it reduces energy yields of methane and sulfide control system that increases the costs of anaerobic systems [60, 74, 75]. In two-stage systems, sulfate is reduced jointly by sulfate reducers in both reactors. Researchers found that domestic wastewater contained 63 mg sulfate/L, and half of sulftate was reduced in AFBR, and the remainder was removed in AFMBR [59, 61]. Sulfate removal is significantly dependent on temperature, and methane producers have the advantage of low temperature conditions. Shin et al. (2014) reported that sulfate reduction efficiency declined to 68% in induvial AFMBR and to 80% in a two-stage system in winter conditions, while all sulfates in both systems were removed in other seasons [45]. Sulfate reduction consumes available COD inside the reactor and reduces the energy production potential. However, researchers have reported several different ratios for COD consumption by sulfate reducers. Although Yoo et al. (2012) stated that sulfate reduction consumed 35% of COD, Yoo et al. (2014) reported that 15% of COD was directed to sulfate reduction [59, 61]. Shin et al. (2014) reported the lowest ratio of 10-11% [45]. During the treatment of municipal wastewater in two-staged AFMBR at 20°C, 95% sulfate was removed while 20% of COD was consumed by sulfate reducers [47]. Unlike others, Dutta et al. (2014)at HRT of 1.28 h and OLR of 5.65kg COD/m(3 indicated that there was no methane production in two-stage AFMBR when sulfate was available in municipal wastewater [63]. The different reported values are associated with the variations in wastewater characteristics, bioreactor configuration and operational conditions. More AFMBR studies in the future with different real wastewater sources will be useful for developing more efficient organic removal strategies.

Fouling Development

Fouling development in AnMBRs is affected by various factors. The content of suspended solid and volatile suspended solids in AFMBR was reported as significant parameters for membrane fouling [44]. In comparison to gas-sparging AnMBRs, single and two-staged AFMBR systems have very low EPS due to low VSS amount in the reactor bulk content [37]. Cake formation is easily formed due to biofoulant deposition on membrane. Researchers found that cake layer was the dominant fouling mechanism in single-stage AFMBR, and its contribution increased with the increased flux [47, 56]. Düppenbecker et al. (2017) observed rapid cake layer formation on ceramic membrane in the absence of fluidization. In comparison with ceramic membranes, cake layer fouling is more significant for polymeric membranes and it forms more rapidly on hydrophobic membranes [47, 48]. Aslam et al. (2018) conducted an analyses that found that biofoulant on the membrane was mainly composed of proteins, carbohydrates, nucleic acids, fatty acids and amide [70].

Organic compounds are diffusing into pores in initial stages of filtration and causing pore fouling, and it could be more affective on membrane performance than cake layer fouling [42, 55, 57]. In comparison to cake layer, the removal of internal fouling is more difficult and chemical cleaning could be useful. Mechanical problems during AFMBR operation may also induce reversible fouling. Mechanical failure of the recirculation pump stopped GAC fluidization and significantly increased TMP, and systems continued operation after chemical cleaning. The increase in TMP was higher in the single-stage then two-staged AFMBR, which was likely related to higher organic loading [37]. Breaking GAC particles by recirculation pump may overflow into the recirculation line and increase TMP [36]. Yoo et al. (2014) reported that the pumping problem may cause incomplete GAC fluidization and rapid increase in TMP, whereas 2 hours of relaxation recovered reactor performance [61].

Bae et al. (2014) compared the single and two-stage AFMBR performance for the treatment of synthetic wastewater at 25°C. They found that single stage was more vulnerable to membrane fouling due to high biomass, while two-stage had more stable operation [37]. Membrane characteristics and pore size affect fouling development. Seib et al. (2016) configured AFMBR with PVDF and ceramic (Al_2O_3) tubular membranes and obtained similar fouling rates during the treatment of synthetic solutions [48]. Similarly, Ahmad et al. (2018) observed similar fouling rates for uncoated and coated ceramic membranes [57]. Düppenbecker et al. (2017) reported that fouling rates of the ceramic UF membrane were lower than MF membrane [47]. The rejection performance of the MF membrane was lower than UF membrane but increased with increasing membrane fouling due to the diminished pore size of the MF membrane. It has been found that deposition of dissolved and colloidal organic matter into the ceramic MF membrane pores caused internal fouling, but ceramic UF membrane was free of internal fouling [68].

Changes in operational conditions are effective on fouling development. During the treatment of real wastewater, fluctuations in OLR and particulate matter accelerate fouling in membrane [68]. HRT significantly affects fouling since solids are easily accumulated on membrane surface at the higher flux and increased TMP across the membrane. At short HRT, the increase in suspended and volatile suspended solids caused an increase in proteins and carbohydrates, which increases membrane fouling [44, 55]. Gao et al. (2014) measured three times higher TMP values at HRT of 4 h than HRT of 6 h [46]. Researchers observed the accumulation of proteins and carbohydrates in AFMBR during the treatment of both synthetic and real wastewater.

Although operation at short HT creates elevated stress on biomass and caused an increase in accumulation of proteins and carbohydrates, AFMBR systems contain fewer foulants compared to gas-sparging MBRs [37, 55]. During the treatment of benzothiazole in a mesophilic IAFMBR, an adverse effect of higher benzothiazole concentration on membrane fouling was observed [67]. Kim et al. (2016) applied the AFMBR for MFC effluent at relatively short HRTs of 1.4 to 3.8 h and did not obtain any increase in fouling, but accumlation of solids inside the reactor slightly increased TMP [66].

In comparison to mesophilic conditions, low temperature accelerates membrane biofouling. Membranes suffer from severe fouling at lower temperatures because of decreased biodegradation rates, reduced back-transport of fouling materials from the membrane surface, increased viscosity, and higher deflocculation rate [15, 76]. Reduction of temperature from 35ºC to 25ºC did not cause important fouling on AFMBR, but there was severe fouling at 15ºC [50]. Similarly, membrane fouling increased TMP six times when temperature was decreased from 15ºC to 10ºC during the treatment of domestic wastewater by two-staged AFMBR [61]. At ambient conditions relaxation can be useful for fouling mitigation, but its effect is decreased at lower temperatures. Yoo et al. (2014) reported that the reactor was operated foul-free in the long term at 25ºC without chemical cleaning [61]. Then temperature steadily decreased until 10ºC, while efficiency of relaxation reduced and TMP increased sharply. For efficient operation of AFMBR at lower temperatures, operation of AFMBR at lower flux would be useful.

Fouling Mitigation

Relaxation has been commonly used to mitigate fouling in membrane systems. In an AFMBR operation, TMP returned to its previous level after 2 h membrane relaxation period at 25ºC [61]. Shin et al. (2014) operated the reactor for 485 days without chemical cleaning with the help of GAC fluidization and relaxation [45]. Yoo et al. (2012) the average effluent chemical oxygen demand and biochemical oxygen demand concentrations of 25 and 7 mg/L yielded corresponding removals of 84% and 92%, respectively. Also, near complete removal of suspended solids was obtained. Biosolids production, representing 5% of the COD removed, equaled 0.049 g VSS/g BOD_5 operated the AFMBR continuously for 192 days while other researchers operated over 310 days without the need for fouling control [45, 59, 61]. However, membrane relaxation was effective for only a limited period if there was irreversible fouling [61, 63]. When membrane relaxation alone is not effective, it could be combined with other methods. Researchers reported that periodic maintenance cleaning and membrane relaxation effectively reduce fouling rate [48, 55]. Applying chemical cleaning is effective in mitigating irreversible fouling, while applied chemicals have been reported without adverse influence on biological activity in AFMBR [61,70]. Aslam et al. (2018) compared the performances of physical cleaning, maintenance cleaning and recovery cleaning on fouling mitigation. Recovery cleaning achieved the highest 93% permeability recovery while maintenance cleaning had 81% improvement. Mechanical cleaning was quite lower than other two methods with 58% efficiency [70]. These figures indicate that recovery cleaning was very successful for the removal of biofoulants. In the absence of fluidizing materials the development of fouling accelerates and severely affects membrane performance. It has been reported that liquid recirculation alone, even at high recirculation flow rate (15 L/min), was not effective in reducing membrane fouling [43]. Researchers stated that fluidization of materials is very efficient in reducing membrane fouling and enables long-term AFMBR operation without significant membrane fouling [53, 57, 59, 66].

The addition of fluidized solid materials creates strong shear force in the reactor and mitigates fouling that is accompanied mainly by mechanical scouring. Characteristics of membrane and fluidized materials play different roles in fouling control. In comparison to hollow-fiber membranes, mechanical scouring is more efficient on flat-sheet membrane due to better access of fluidized materials to membrane surface [41]. Wang et al. (2018) indicated that sphericity is less effective than the size of fluidized material on fouling mitigation efficiency [77]. Higher sphericity enhances fouling mitigation media, and particle sphericity is a negligible factor in the energy efficiency of fouling control. On the other hand, the size of solid particles is more efficient than density on effective fouling mitigation by mechanical scouring [42]. Cahyadi et al. (2017) performed a detailed study on hydrodynamics in AFMBR and found that both water and particle velocities move non-uniform vertically and laterally, and this causes non-uniform distribution of fouling across the membrane [35]. Efficient fouling management calls for determining fouling mechanisms and selecting proper fluidized solid material. Researchers have proposed a model to predict dominant fouling mechanisms by assessing fouling resistance caused by cake formation and pore blocking separately [41, 42]. The model fit well to the experimental data obtained with a lab-scale AFMBR operated during 250 days under different operational conditions. The model is useful for determining the dominant fouling mechanism and to select optimum fluidized material for effective foulant mitigation.

Using Fluidized Solid Materials for Fouling Mitigation

So far, various fluidized solid materials have been used in AFMBR studies. With efficient scouring effect, glass beads are successful in mitigating cake layer from ceramic membranes and providing higher run-time in two-stage AFMBR. Glass beads with a diameter of 1.5 mm and 74% bed voidage have been proposed for efficient treatment of municipal wastewater [47]. Polyethylene terephthalate (PET) beads have advantages of uniform spherical shape, low specific gravity and less energy demand [40, 42]. A comparative study revealed that the addition of PET to gas flowing decreases the fouling rate and achieves 30% more TMP reduction efficiency compared to gas sparging only. In comparison to gas sparging alone, the addition of PET reduces the gas sparging rate by 67% and energy consumption by 90% during the fouling mitigation from PVDF hollow-fiber membranes [40]. Researchers have reported that single PET was not efficient on the mitigation of fouling caused by organic colloids, but the addition of gas sparging to PET recirculation increases performance. In their study, Aslam et al. (2014) compared the performance of silica, GAC and PET beads. Smaller fresh GAC particles provided the best fouling mitigation efficiency, whereas silica particles and PET beads demonstrated similar results to pre-adsorbed GAC. Moreover, silica particles consumed more power for fluidization because of their higher specific gravity [43]. In comparison to silica, PET performed better mechanical souring of fouling due to bigger size [42]. Different mechanisms play roles alone or synergistic in fouling mitigation by activated carbon in AFMBR. Great surface area of activated carbon enables adsorption of various pollutants and development of biofilm for biodegradation of pollutants, but mechanical scouring is the dominant factor in fouling mitigation. When freshly activated carbon is used, membrane fouling is reduced, whereby both adsorption and mechanical scouring but relative benefit of each factor depends on operation time. In early stages adsorption is effective at fouling mitigation and its effect is higher at smaller GAC size [43]. However, fresh particles are saturated within 1 h and mechanical scouring becomes a dominant mechanism in AFMBR [51, 43]. However, fouling is mainly controlled by mechanical scouring and its impacts increase with size in the case of pre-adsorbed activated carbon.

In AFMBR operation, significant removal of pharmaceuticals and organics from domestic wastewater was obtained due to higher sorption capacity [63]. On the other hand, GAC fluidization also improved run-time of AFMBR operation and enhanced critical flux by about 46-50% [64, 57]. Fouling mitigation performance of GAC is also affected by membrane properties. Researchers achieved 55% and 120% longer run-times during the treatment of primary wastewater by using ceramic and polymeric membranes, respectively [48]. It has been found that the addition of little biogas into fluidization of GAC with liquid recirculation was very efficient at all HRTs tested and it also extended the membrane fouling time by 2.1 times [53]. In general, adsorption capacity and scouring effect are surged by higher GAC dosages and packing ratio. Researchers concluded that contents of both EPS and SMP in mixed liquor in the reactor and development of cake layer on the membrane decreased with the increase in GAC dosage [46]. Aslam et al. (2014) investigated the effect of packing ratio of GAC on AFMBR performance [43]. They found that 70% packing ratio did not achieve more fouling mitigation than 50% packing ratio for all GAC sizes tested. Besides, higher packing ratio increased energy demand in AFMBR operation. Therefore, assessment trade-off between fouling mitigation and energy consumption should be done for the selection of optimum packing ratio during AFMBR design. Placing hollow-fiber membranes also affects fouling mitigation success. GAC size is important on optimal hollow-fibre spacing and it is more significant on cake layer fouling reduction at longer spacing. Large GAC particles, higher packing ratio and 3-5 mm hollow fibre spacing were recommended as being beneficial for efficient fouling mitigation [51].

The size of GAC particles plays a critical role on fouling control and treatment performance of AFMBR. In general, scouring is more efficient with large GAC, while adsorption is higher with smaller particles [33, 56]. Wang et al. (2016) compared three GAC sizes of 1.20 mm, 1.85 mm and 2.18 mm, and found that the smallest particle provided decreased scouring efficiency while larger particles had similar fouling mitigation performance [78]. In their study, Hu and Stuckey (2007) examined the effects of PAC and GAC on flux changes and treatment efficiency [49]. PAC achieved higher membrane flux and lower TMP with 22.4% higher COD removal efficiency, while there was no significant improvement in the reactor with GAC. Cake layer was removed by scouring from membrane surface, and sorption of dissolved organics improved the fouling control. Wu et al. (2014) monitored how the relatively bigger foulant flocs were easily removed from the membrane with the help of GAC scouring [79]. On the other hand, fine GAC particles have an insignificant effect on mechanical scouring, especially if the size is less than 0.5 mm [41].

Releasing small GAC particles due to abrasion accelerates membrane fouling and causes a decline in membrane filtration performance. At the same time, microbial flocs and large colloidal aggregates in the reactor could be broken with the collision of fluidized solids [79]. Shin et al. (2016) reported that pore clogging with fine particles was more significant than membrane damage on fouling development [72]. The deposition of fine carbon particles on the membrane surface increases irreversible fouling and reduces fouling mitigation efficiency [73, 80]. Researchers found that GAC particles of less than 0.5 mm have more contribution on cake formation on membrane surface [41]. Pore blockage due to entrapped particles cause a black colour on membrane surface and cannot be easily removed by chemical cleaning [65, 72]. During the treatment of organics, the development of fine GAC particles needs to be avoided since GAC particles have higher affinity to organic pollutants and they become stronger foulants on membrane pores together [51]. Although large fluidized particles are very effective on fouling mitigation by scouring, they induce more damage on membrane integrity than small particles.

Loss in membrane integrity due to the direct contact of fluidized solids with membrane surface is a major concern that reduces membrane lifetime and increases cost. Membrane damage by fluidized materials is severe in the early stage of filtration during the absence of cake layer [51]. Shin et al. (2016) developed a simple procedure to control the integrity of hollow-fiber membranes in a short time. Test results highlighted how the integrity of membranes manufactured with the same materials and processes varies considerably between manufacturers [65]. Contradictory results about the effect of fluidized materials on membrane integrity have been released. Some researchers have reported that PET and GAC did not cause damage to hollow-fiber membranes [40, 54]. However, Shin et al. (2016) operated a pilot-scale AFMBR configured with PVDF hollow-fiber membranes for more than two years and highlighted how GAC induced considerable damage to membrane [65]. Interestingly, the extent of damage was significantly related to the membrane position in the reactor. Continuous physical contact with larger and more densely packed GAC particles created more severe damage in the bottom of the membrane. Additionally, damage to the rear of the reactor is bigger than the middle or front of the reactor due to higher upflow velocity created by short-circuiting by fluid. The most harmful damage to membranes was reported with the use of glass beads. Fluidized glass beads damaged all the ceramic membranes tested by abrasion, and the extent of damage differs among the membranes [47, 68]. In the case of MF, 75% of the initial thickness of active layer was removed. Although the active layer of UF was seriously damaged, soluble COD removal performance did not significantly change with the help of filtration by support membrane. Researchers indicated that ceramic Al_2O_3 MF membrane with pore size of 0.1 µm had no damage and is a promising alternative for AMBR configuration. Comparative studies have revealed that large GAC particles have greater impact on membrane damage. Shin et al. (2016) found that large GAC particles (2.0-4.0 mm) induced greater damage on membrane and increased pore sizes of membranes five times higher than small particles [72]. Similarly, larger glass beads (1.5 mm) caused more severe damage than small beads (0.8-1.2 mm) [68].

Microbial Community

During the treatment of wastewater by anaerobic community, organic matters are converted to biomass, methane-rich biogas and volatile fatty acids. The rich microbial community and higher biomass amount provide better treatment efficiency while organic removal in AFMBR could be insufficient in the case of limited biomass. Real wastewater may contain high TSS and VSS while biomass production is higher than synthetic wastewater. In AFMBR systems, bulk VSS amount is relatively low since most biomass is grown as biofilm on GAC particles. AFMBR systems have the advantage of less sludge production than other biological systems. VSS concentration in gas-sparging anaerobic MBRs reported over 5000 mg/L, whereas AFMBR has a much smaller VSS amount of about 500 mg/L in AFMBR [55, 81]. Additionally, comparing biomass production per unit $COD_{reduced}$ amount indicates that AFMBR is favorable over other MBR systems. Yoo et al. (2012) the average effluent chemical oxygen demand and biochemical oxygen demand concentrations of 25 and 7 mg/L yielded corresponding removals of 84% and 92%, respectively. Also, near complete removal of suspended solids was obtained. Biosolids production, representing 5% of the COD removed, equaled 0.049 g VSS/g BOD(5 indicated that biomass amount was 0.031 g VSS/g $COD_{removed}$, which is one-tenth the aerobic system [59]. Bae et al. (2014) obtained 0.002-0.003 gVSS/g$COD_{removed}$ with single- and two-stage AFMBR application on low-strength wastewater [37]. Other researchers have reported lower biomass production of less than 0.05 g VSS/g $COD_{removed}$ in different AFMBR systems, which are lower than other MBR systems [58, 61, 63, 70, 82].

Bioreactor configuration and variations in operational parameters are influential on biomass growth. More portion of organic matter is directed to biomass growth at long HRT, whereas VFAs are accumulated when AFMBR is operated on short HRT [46]. At low temperature the amount of sludge is higher and VFAs are accumulated in AFMBR since hydrolysis of colloidal materials and complex organics are slower [45, 61]. On the other hand, researchers have obtained steady improvement in microbial acclimation and reactor performance with the increase in operational temperature [45]. GAC has high surface area and is a more favorable place for methane producers than the bulk liquid. More of the active biomass was found attached on GAC particles in AFMBR, and biofilm has high resistance against the changes in environmental conditions [59, 37]. During the operation of AFMBR at short HRT, bulk VSS may wash out easily, but attached biofilm stayed on GAC surface and provided higher treatment efficiency. Biofilm contains diverse microorganisms, and methanogens are very sensitive to changes in temperature. Hydrogen-consuming methanogens favour psychrophilic conditions and their abundance significantly increased when temperature was reduced from 25ºC to 10ºC, and acetate-consuming methanogens are found to be rate-limiting on organic degradation from domestic wastewater [50]. During the treatment of benzothiazole in IAFMBR, acetotrophic methanogens were always dominant; however, the ratio of hydrogenotrophic methanogens increased from 8.7% to 16.9% with the increase in organic loading [67].

Anaerobic reactors are dominated mainly by a few bacterial communities and have greater richness than archea in AFMBR [12, 83]. The microbial community on GAC and in suspended sludge within AFMBR could be different. Clostridium, Bacteroides, Cytophaga, Geobacter and Trichococcus were relatively dominant in microbial biomass, while Methanosaeta, Methanobacteriu and Methanospirillum were abundant in the archaeal community during the treatment of synthetic wastewater [12, 67]. Among them, Methanosaeta favours living on GAC and produces methane by acetate consumption. However, changing feed to domestic wastewater altered microbial diversity in AFMBR due to continuous feeding of microorganisms with wastewater. Clostridium is active in degrading complex organics, and it was dominant in IAFMBR treating benzothiazole at all conditions, but its relative abundancy decreased at lower HRT. At the same time, acetotrophic methanogens increased with the reduction in hydrogenotrophic methanogens while it decreased when HRT was reduced from 24 h to 12 h [69]. Cheng et al. (2018) found that Methanosaeta was dominant on GAC while Methanosaeta, Methanomethylovorans, and Methanosarcina were abundant in suspended sludge [44]. Arcobacter, Bacteroides, Parabacteroides, and Aeromonas were dominant in AFMBRs [54]. Li et al. (2017) indicated that Pseudomonas were abundant and very effective in the treatment of benzothiazole in a mesophilic IAFMBR [67]. Compared to the bacterial community, archaeal diversity is almost the same in all operational conditions. Aslam et al. (2018) identified many different bacteria in both bulk and GAC surface [70]. Among them, Proteobacteria are associated with the development of biofilms on the fluidized GAC particles, and Firmicutes accelerate biofouling. Geobacter- and sulfate-reducing bacteria are more abundant on GAC than reactor fluid during the treatment of domestic wastewater [52, 54]. The presence of Geobacter is related to the extracellular electron transfer for acetoclastic methanogens and induced abundance of Methanothrix, which is an acetoclastic methanogen in AFMBR [54].

Energy Requirement and Production

The major advantage of AFMBR is less energy consumption than other MBR systems. Researchers reported that single and even two-stage AFMBR systems require lower energy than biogas-sparging AnMBRs [36, 55]. Ye et al. (2016) estimated operational energy demand as 0.06 kW h m^{-3}, which is about one-tenth the requirement of other AnMBRs [54]. In AFMBR systems, energy demand is mainly related to fluidization of materials and this could be higher by up to 95% of total energy consumption [47]. Hydraulic headloss associated with membrane permeation and piping headloss also contribute to energy consumption, and the majority of headloss resulted from minor losses in conduit connections. The combination of narrower membrane tube diameter, multiple membrane tubes, and additional hose bends and connections for multiple membranes has resulted in higher headloss in polymeric systems [48]. Energy demand for permeate pumping from MF was found to be higher than UF due to clogging [47]. Increasing cross-flow considerably increased energy usage, and Seib et al. (2016) indicated that energy consumption during high crossflow (3-5 m/s) operation was at least 30 times greater than low crossflow (0.018-0.3 m/s) operation [48]. Membrane material could be another factor in energy usage, and ceramic membranes have less headloss than polymeric membranes, since ceramic modules have a single membrane tube.

In two-stage systems, AFMBR is mostly operated with AFBR. In AFMBR operation solid materials are completely fluidized to cover membrane surface, but AFBR is operated under incomplete fluidization. Moreover, a small amount of additional electrical energy is used for AFMBR permeate pumping. Researchers compared the energy demands for both reactors and reported different values. Bae et al. (2013) calculated three-fold higher energy usage for AFMBR than AFBR, but Shin et al. (2014) reported 10 times higher energy consumption for AFMBR [45, 60]. This difference is associated with the variations in specific gravity of GAC and fluidization ratios. Higher material size, packing ratio and specific gravity require higher recirculation flow rate and energy consumption [39]. Düppenbecker (2017) reported that increasing the size of glass beads from 1 mm to 1.5 mm increased energy consumption by about 25% [68]. In the study of Aslam et al. (2014), they concluded that energy requirement for GAC fluidization grows exponentially with the increase in particle size, and larger materials with lower specific gravity provide more energy efficiency in fouling mitigation [43].

AFMBR systems can be operated in a more energy-efficient way by converting methane to electricity. Various energy recovery ratios have been estimated for different AFMBR systems. Aslam et al. (2017) calculated that produced methane has 5.8 more energy potential than that required for the operation [55]. In a different study by Aslam et al. (2018), energy content of methane produced in AFMBR was predicted to be 9.8 times more than operational requirement [70]. Yoo et al. (2014) estimated that energy potential of gaseous and dissolved methane from domestic wastewater with influent COD of 235-300 mg/L is 3.7 times higher than energy demand for AFBR+AFMBR at 10ºC [61]. Ren et al. (2014) operated MFC and AFMBR together and estimated that energy produced by only MFCs (0.0197 kWh/m^3) is theoretically sufficient to meet the energy demand in a two-stage system (0.0186 kWh/m^3) [62]. Similarly, Kim et al. (2016) produced sufficient energy in MFC operation to supply pumping energy of AFMBR [66]. However, other researchers have found that energy content of gaseous methane can offset between 30% to 64% of total energy consumption in different AFMBR systems [48, 60, 68]. The variations in energy consumption and recovery values are related to the different headloss in reactor components and varied methane production efficiencies from different operational conditions. In relation to energy recovery in AFMBR, loss of dissolved methane in liquid phase is a big concern. The amount of methane loss is increasing at lower operational temperatures. Researchers calculated that the proportion of dissolved methane in winter (61%) was higher than in autumn (28%) [45]. Gao et al. (2014) found that dissolved CH4 increased slightly from 21.6% at 35ºC to 28.6% at 25ºC, but a considerable increase was at 15ºC with to 45.2% [50]. Researchers predicted that 43-50% of the total methane left the reactor dissolved in the permeate during the treatment of domestic wastewater [47, 68]. Future studies should focus for the development of new applications to improve the energy efficiency of AFMBR operations.

Conclusions

Anaerobic fluidized membrane bioreactors can be operated in the modes of single-stage or two-stage for the treatment of wastewater. AFMBR systems have shown great performance for effective removal of pollutants and efficient fouling mitigation. The development of fouling in AFMBR is associated with bioreactor configuration, membrane properties and operational conditions. Fluidized solid particles remove foulant from membrane mainly by mechanical scouring along with the contributions of adsorption and biodegradation mechanisms. The effective operation of AMBR systems has been proven on domestic wastewater and some industrial wastewater, while future studies need to use different feed wastewater. In the case of GAC usage, biodegradation of pollutants is very effective and microbial diversity is significantly affected by the changes in operational conditions. The results of this review indicate that future efforts should be directed to the treatment of different industrial wastewater and recovery of dissolved methane to extend the applications of self-energy-efficient AFMBRs.

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