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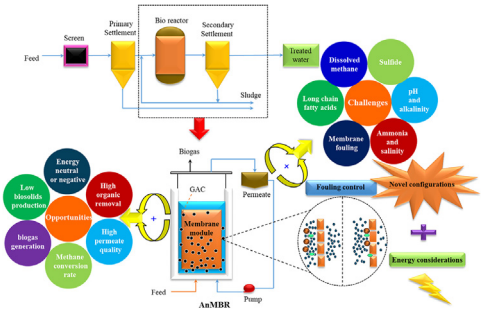
Review

Anaerobic membrane bioreactors for wastewater treatment: Novel configurations, fouling control and energy considerations

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GRAPHICAL ABSTRACT



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ABSTRACT

Water shortage, public health and environmental protection are key motives to treat wastewater. The widespread adoption of wastewater as a resource depends upon development of an energy-efficient technology. Anaerobic membrane bioreactor (AnMBR) technology has gained increasing popularity due to their ability to offset the disadvantages of conventional treatment technologies. However there are several hurdles, yet to climb over, for wider spread and scale-up of the technology. This paper reviews fundamental aspects of anaerobic digestion of wastewater, and identifies the challenges and opportunities to the further development of AnMBRs. Membrane fouling and its implications are discussed, and strategies to control membrane fouling are proposed. Novel AnMBR configurations are discussed as an integrated approach to overcome technology limitations. Energy demand and recovery in AnMBRs is analyzed. Finally key issues that require urgent attention to facilitate global penetration of AnMBR technology are highlighted.

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1. Introduction

The scarcity of water resources and environmental consequences caused by the addition of wastewaters into main water bodies and soil has triggered the need of treating wastewater. Currently, wastewater serves as a source of clean water and a valuable resource for renewable energy (biogas) and nutrients (fertilizers) (McCarty et al., 2011). The practicality of using wastewater as a resource lies in the development of an efficient, economical and environmental friendly treatment technology (Khan et al., 2016). Aerobic wastewater treatment technologies have been in use since a century. However, these methods require high energy, produce high amount of sludge, need of larger space for plant operation and higher maintenance cost which offset the advantages of reusing wastewater (Krzeminski et al., 2017). During the process, there is uncontrolled release of methane (CH_4), carbon dioxide (CO_2), and nitrogen oxide (N_2O) which are potent greenhouse gases (Foresti et al., 2006; Ghauri et al., 2011). Hence, there is an immense need of developing alternate wastewater treatment technology. Recently, membrane separation processes gained significant attention to recover resources from waste streams, biofuels and especially wastewater to reduce potent greenhouse gases (Khalid et al., 2019; McCarty et al., 2011).

Anaerobic membrane bioreactors (AnMBR) are emerged as a promising alternative to aerobic wastewater treatment technologies. AnMBR have low energy input, and sludge production compared with aerobic processes. Furthermore, employing AnMBRs reduce: the operational space, and number of unit operations compared with conventional processes (as shown in Fig. 1). The also offer easy scale-up and selective separation and recovery of nutrients and resources (Aslam et al., 2018b; Liao et al., 2006). However, widespread adaption of technology is still hindered due to several issues including membrane fouling, dissolved CH_4 recovery, sulphide-induced low COD and alkalinity. Among these, membrane fouling is a key bottleneck for their commercialization (Lin et al., 2013).

Membrane fouling gradually decrease the permeate flux and efficiency of treatment process. Various strategies have been adapted to overcome membrane fouling (Shoener et al., 2016). Novel AnMBR configurations are introduced to overcome the issues in scale-up of technology in general, and combat membrane fouling in particular. These reactor schemes have also reduced the energy input and increase the CH_4 production yield (Shin and Bae, 2018; Smith et al., 2014). So far, a number of review papers have been published on AnMBRs for wastewater treatments (Lin et al., 2013; Ozgun et al., 2013; Shin and Bae, 2018; Skouteris et al., 2012; Smith et al., 2012; Stuckey, 2012). The potentials of novel AnMBR configurations were not enlightened and the research works related with AnMBRs were partly enunciated in the previous reviews. Moreover, there are several hurdles, yet to climb over, for wider spread, optimization of design configuration, economic feasibility and scale up of the AnMBR technology. Therefore, a critical review on recent technical innovations and emerging configurations to improve energy production potential and achieve energy neutrality or positivity is of crucial importance particularly in AnMBRs.

This review covers fundamental aspects of anaerobic digestion of wastewater and novel configurations, fouling control and energy considerations in AnMBRs. This study identifies the major challenges and opportunities in wastewater treatment using AnMBRs. Novel AnMBR configurations to combat membrane fouling are presented. Energy demand and recovery in AnMBRs is analyzed. Finally, key issues that require urgent attention to facilitate global adaption of AnMBR technology are highlighted.

2. Fundamentals of anaerobic membrane bioreactors

2.1. Technical overview

AnMBR technology is a promising to treat wastewater and recovery of resources such as bioenergy in the form of renewable methane, fertilizing elements it contains and water for reuse to control the pollution in environment and energy sustainability (Charfi et al., 2017b; Smith et al., 2012; Khan et al., 2016). It is a hybrid system in which membranes are combined with anaerobic bioreactor. There are different pathways selected for implementation of membrane in bioreactor or outside bioreactor. Membrane module is present outside reactor and permeate obtains under pressure provided by recirculation pump in external cross flow configuration (Fig. 1b). In this approach, filtration cake on membrane surface is disturbed by cross flow velocity (Skouteris et al., 2012). The drawback of this scheme comes in form of energy consumption by recirculation pump to maintain transmembrane pressure (TMP) and elevated volumetric flow to keep cross flow velocity at certain level. However, membrane cleaning is easy because membrane can easily be taken out for cleaning purposes (Szentgyörgyi and Bélafi-Bakó, 2010). An external membrane module system is easy to monitor and maintain. However, more energy is required in this configuration with high hydraulic shear force which might damage the favorable anaerobic solid microbes into small sizes and causes membrane fouling. Operating TMP and cross flow velocity through membrane in external membrane module is relatively high (Berube et al., 2006). In contrast, with submerged AnMBR, membrane module is directly immersed in bioreactor and treated water obtains under vacuum pump or gravity on permeate side of membrane and retained biomass presents in bioreactor. (Fig. 1c). In this approach, biogas is used to mitigate cake formation (Shin et al., 2016b). Submerged AnMBR is more favorable for low strength organic loads like municipal wastewater (Musa et al., 2018). In this system, cross flow velocity and TMP are relatively low. Gas is entered into the system at base of membranes. The gas bubbles carry liquid upward and causes cross flow along membrane (Berube et al., 2006). In external submerged configuration, membrane is present in separate tank outside bioreactor and needs pump to return retentate to bioreactor as shown in Fig. 1d (Liao et al., 2006). Membrane operates under vacuum in this configuration. In all these techniques, difference is in direction of flow that reverts and as result different TMP is obtained (Singhania et al., 2012).

2.2. Chain of processes in anaerobic membrane bioreactor

Anaerobic treatment of wastewaters involves a logical sequence of processes starting with hydrolysis as shown in Fig. 2. During this process, small water soluble compounds are attained by the breakage of complex organic matter. The complex molecules contain proteins, carbohydrates and fats, which are transformed into monosaccharaides, fatty acids and amino acids by facultative and/or obligate anaerobic hydrolytic bacteria (Lei et al., 2018). The hydrolytic bacterial species are unique and specifically degrade particular type of macromolecule. The hydrolysis rate depends on the temperature, pH, hydrolyzing mass concentration and size/type of particulate organic matter (Visvanathan and Abeynayaka, 2012).

Acidogenesis is a second step of anaerobic treatment. This process converts soluble sugars, amino acids and fatty acids into short chain volatile fatty acids (VFAs: formic, butyric, propionic, and acetic acid), alcohols, aldehydes, hydrogen and carbon dioxide as shown in Fig. 2. Environmental conditions and bacterial type can vary the characteristics of acidogenic products. Sometimes hydrolysis and acidogenesis can be performed by the same facultative and/or obligate anaerobes e.g. *Clostridium, Micrococcus, Pseudomonas*, and *Flavobacterium* (Xie et al., 2014). Acidogenic bacteria are rapid growing micro-species and are affected by environmental conditions (Visvanathan and Abeynayaka, 2012). The accumulation of VFAs during the process could lead to low pH conditions which are not suitable for the growth of methanogens during the next phase.

Acetogenesis is a third stage of anaerobic treatment process presented in Fig. 2. This process is aided by acetogenic bacteria that convert VFAs, alcohols, and hydrogen into acetate (Xie et al., 2014). The process of acetogenesis is led by two groups of bacteria: oxidation of

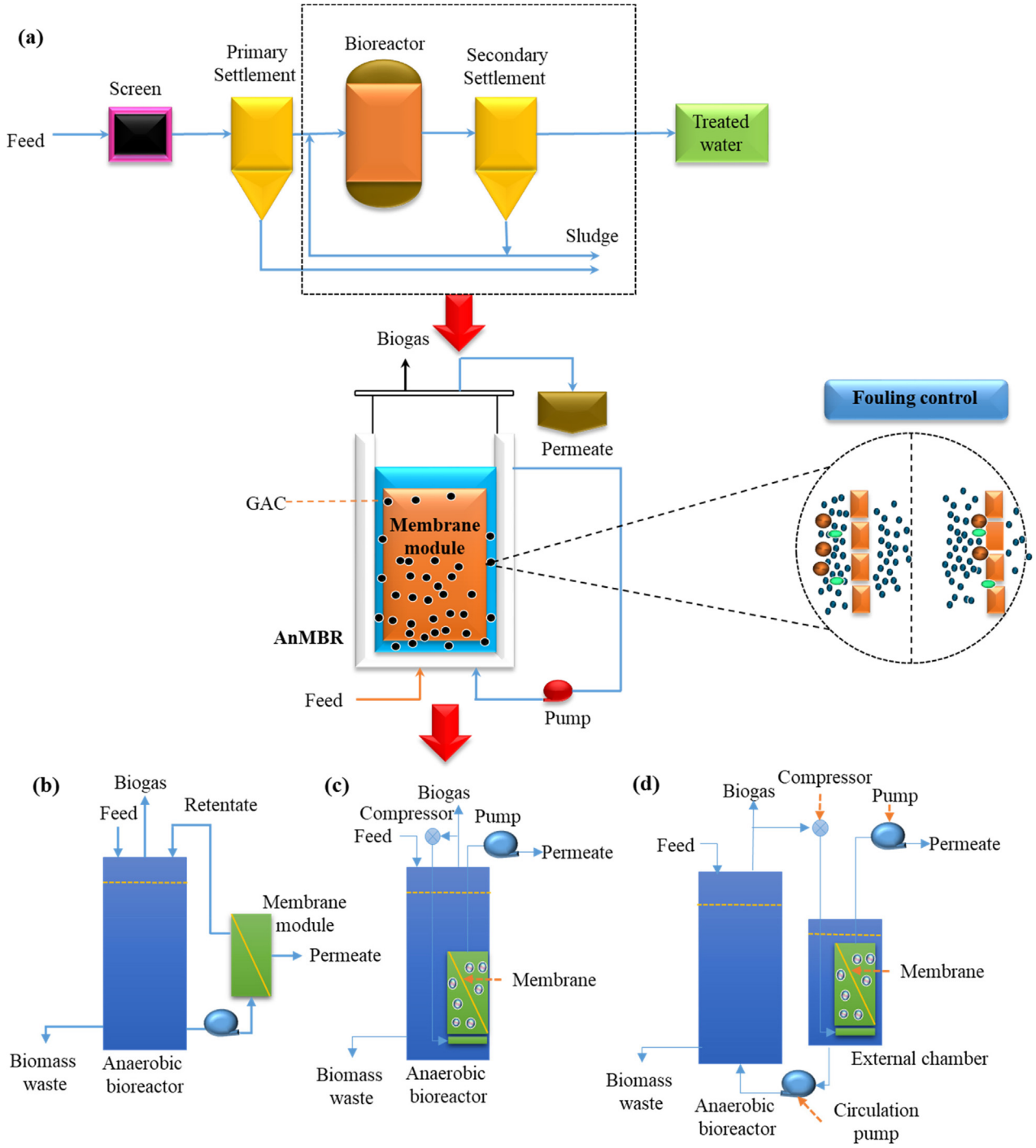


Fig. 1. (a) Anaerobic membrane bioreactor technology in replacement of conventional activated sludge process; (b) Side-stream AnMBR; (c) Submerged AnMBR; (d) External submerged AnMBR.

butyrate, propionate and long chain fatty acids to acetate (obligate H_2 producing bacteria), and intake of H_2 and CO_2 to produce acetate by homoacetogens (Ketheesan and Stuckey, 2015). Homoacetogens also utilize sugar and alcohols, generating acetate and H_2. Acetogenic bacteria include *Clostridium, Acetobacterium*, and *Sporomusa* (Ketheesan and Stuckey, 2015).

Last process during anaerobic digestion is methanogenesis in which methane is produced. Methane production is a two way process in the anaerobic digestion as shown in Fig. 2. In the first way, methane is produced from acetate by aceticlastic methanogens such as *Methanosarcina* and *Methanosaeta* (Ketheesan and Stuckey, 2015). Approximately, 70% methane is produced via aceticlastic methanogenesis. Second way of methane production is through hydrogenotrophic methanogens which converts carbon dioxide and hydrogen to methane and carbon dioxide (Xie et al., 2014). Methanogenic activity is the measurement of methane production rate which depends on availability of methane formers and substrate for methane yield. Any change in methanogenic activity presents obstacle or slow collection of degradable or non-degradable organic load. Methanogens are responsible for methanogenesis (methane production pathway) which are group of archaea (Hussain and Dubey, 2017).

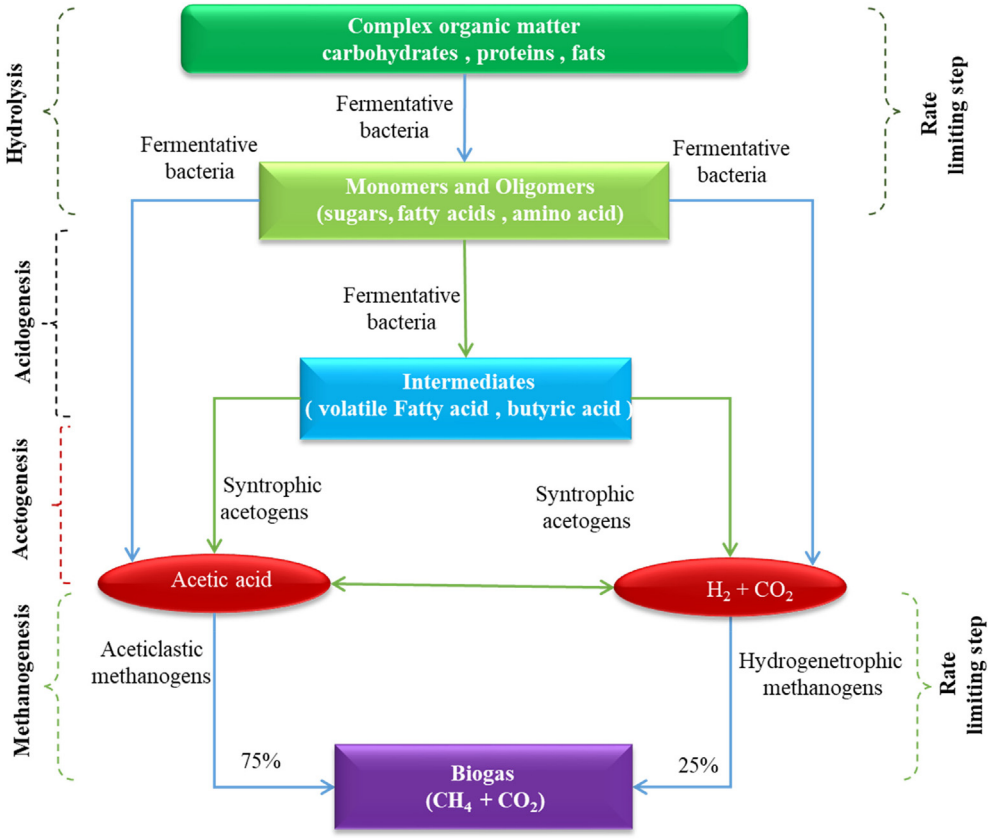


Fig. 2. Anaerobic treatment in AnMBRs.

3. Challenges and opportunities in AnMBRs development

The main challenges associated with scale-up and commercialization as well as achievable benefits by treating wastewaters using AnMBRs are presented in Fig. 3. Among them, fouling is considered as the most important one. This is due to challenges in fouling control and limited life time of membranes. Membranes are still major contributor to capital and operational costs of AnMBRs. In order to implement a proper fouling control system, it is important to understand the type of membrane fouling discussed below.

External fouling occurs by the deposition of particles, colloids, and macromolecules with larger than pore sizes of membrane. It is divided into two types on the basis of layer formation. First one is cake layer which leads to agglomeration of grasp solids on membrane and has reversible character. The other is gel layer, formed by precipitation of soluble macromolecules, colloids, and inorganic solutes (Ruigómez et al., 2016; Wang et al., 2014). Different fouling types are presented in Fig. 4. Internal fouling occurs in the presence of fine particles, solutes, and undissolved matter that are submerged or retained inside the membrane pores. During internal fouling, porous membranes are blocked due to “pore blocking” by particles having an equal or smaller diameter compared with the membrane pores and generates irreversible fouling (Aslam et al., 2018a; Bagheri and Mirbagheri, 2018). During continuous filtration process, direct flow path of foulants to membrane is higher than that due to backflow diffusion to bulk solution before steady state. This phenomenon in which accumulation of rejected components in the form of thin liquid layer occurs adjacent membrane surface called “concentration polarization” and this is a

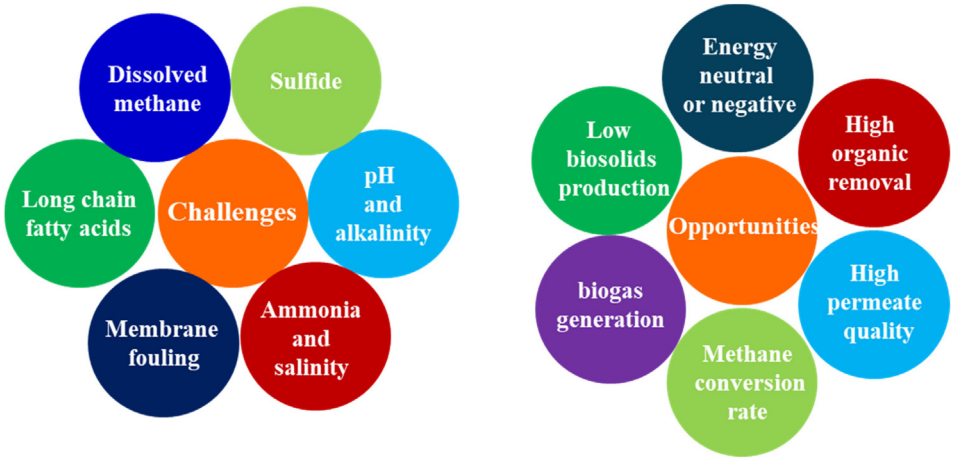


Fig. 3. Challenges and opportunities in AnMBRs.

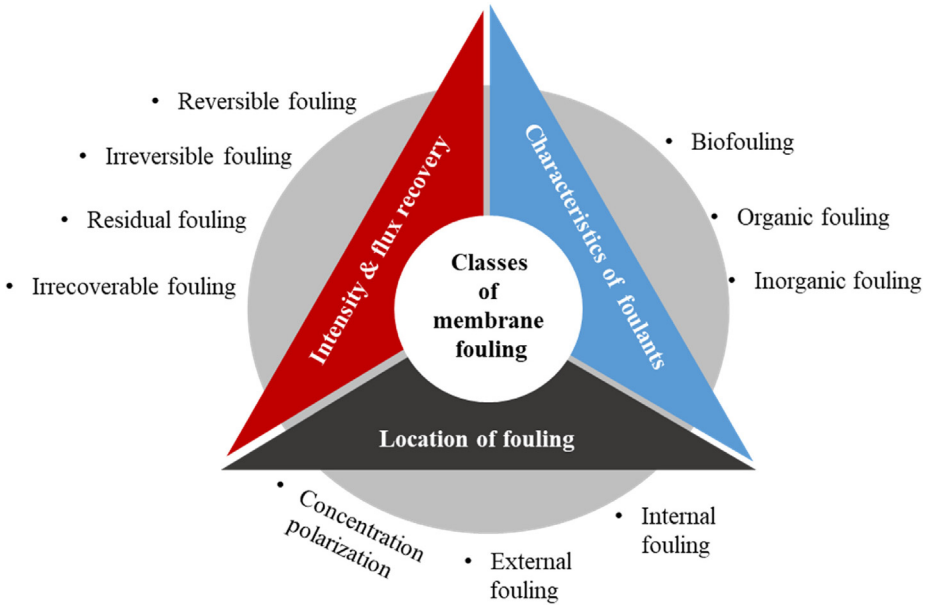


Fig. 4. Classifications of membrane fouling in AnMBRs.

reversible and inherent phenomenon during membrane filtration (Wang et al., 2014).

Membrane fouling can be distinguished in further two types such as reversible and irreversible fouling based on cleaning practice (Lin et al., 2013). Reversible fouling corresponds to cake formation defined as porous layer rejected on membrane surface. Reversible fouling tends to remove by physical means such as relaxation or backflushing (Calderón et al., 2011). Irreversible fouling is a fouling due to pore clogging/blocking or gel layer formation during long-term operation under sub-critical flux conditions, which cannot be diminished by physical cleaning methods. Residual fouling corresponds to accumulation of fat, protein, and minerals that can be linked to different fouling mechanism. This type of fouling can be removed by recovery cleaning but it is difficult to clean residual fouling by chemically enhanced backwashing or maintenance cleaning (Wang et al., 2014). Irrecoverable fouling is associated with long term experiment, when membrane is fouled once then original membrane permeability is never achieved. This remaining resistance is termed as "irrecoverable fouling" and cannot be removed by typical chemical cleaning. It is also called as "long term irreversible fouling" or "permanent fouling" (Wang et al., 2014). Biofouling is the interaction of components of biological treatment broth with the membrane surface. Biofouling also occurred by accumulation of extracellular polymeric substances (EPS) and soluble microbial products (SMP) on membrane and pore surfaces (Aslam et al., 2018a). Organic fouling is caused by accumulation of macromolecular species (biopolymer) and organic constituents on the membrane surfaces (Huang et al., 2011). In contrast, inorganic fouling usually refers to the scalants, inorganic colloids and crystals on membrane and pore surfaces (Stuckey, 2012).

Sulphide concentration cannot be neglected in AnMBRs application for wastewater treatment because of its impact on COD to CH_4 conversion (Chen et al., 2016). The total methane production can be affected by influent sulphate content and thereby enhanced overall operating cost (Pretel et al., 2014). The operating cost of AnMBR by using low or none sulphate content having municipal wastewater was minimized upto 28%. The presence of sulphate can precipitate non-alkaline metals (e.g. Fe and Co) in AnMBRs, which will limit the availability of micronutrients for methanogens. The other disadvantage of precipitation is membrane fouling. H_2S is produced as result of reduction of sulphate which can easily pass through bacterial cell membrane and destroy native proteins inside cytoplasm. The performance of AnMBRs may be defected by competition between sulphate reducing bacteria (SRB) and methane producing archaea (MPA) for present carbon due to faster growth of SRB (Park et al., 2014; Lei et al., 2018; Shin and Bae, 2018). SRB has low response to temperature change, and therefore at ambient temperature, SRB may have more strength for available carbon source. Generally, SRB competes MPA for hydrogen on the basis of available electron donors competition between SRB and MPA; and SRB complete more efficiently for hydrogen than that of MPA (Lei et al., 2018). So, SO_4^{-2}-S induced low COD to methane yield due to competition between hydrogenotrophic SRB and MPA. Because SRB are oxidizers at both low and high COD/SO_4^{2-}-S ratio and acetoclastic MPA is dominant at high ratio, so there is lack of hydrogen for hydrogenotrophic MPA and SRB. This will increase conversion of COD to methane (Giménez et al., 2012; Lei et al., 2018). Generally, maintaining low sulphate concentration at optimum point is necessary in AnMBRs.

An appropriate pH range is important factor for efficient methanogenic digestion system. Values outside this range can be harmful for system especially to methanogenesis, so it is important to control pH for AnMBR system. The operating temperature and nature of wastewater affect the pH and alkalinity in the system. Nevertheless at temperature below 20 °C, gaseous compounds become more soluble. So it means that reactor pH goes down due to dissolved amount of hydrogen sulphide and carbon dioxide under psychrophilic condition (Lei et al., 2018). Shin et al. (2014) observed that pH range and alkalinity remain same at 6.6–6.8 and 220–260 mg$CaCO_3$ L^{-1} respectively in both staged reactors with 4.6–6.8 h hydraulic retention time (HRT) and average COD of 198–285 mg/L (Shin et al., 2014). Many studies indicated that methane production mostly occurs at pH ranges from 6.5 to 8.5 and the process is badly affected by pH below 6.5 or rises above 8.5 (McCarty and Rittmann, 2001; Weiland, 2010). The major controlling parameters in methanogenic process are carbonic acid related system, mainly HCO_3^-, and its concentration equals total alkalinity (McCarty and Rittmann, 2001).

The major byproduct of AnMBR is the methane gas produced during biodegradation of organic matters (Khanal, 2008). Methane gas is a major constitute of greenhouse gases and has the potential of aggravating global warming 25 times more than carbon dioxide (McCarty et al., 2011). Due to this reason, emission of methane should be controlled. Methane in gas form is easy to capture, but it is difficult task to collect it in dissolved form. Methane solubility is more at 15 °C as compared to 35 °C (Smith et al., 2012). It was reported that half of

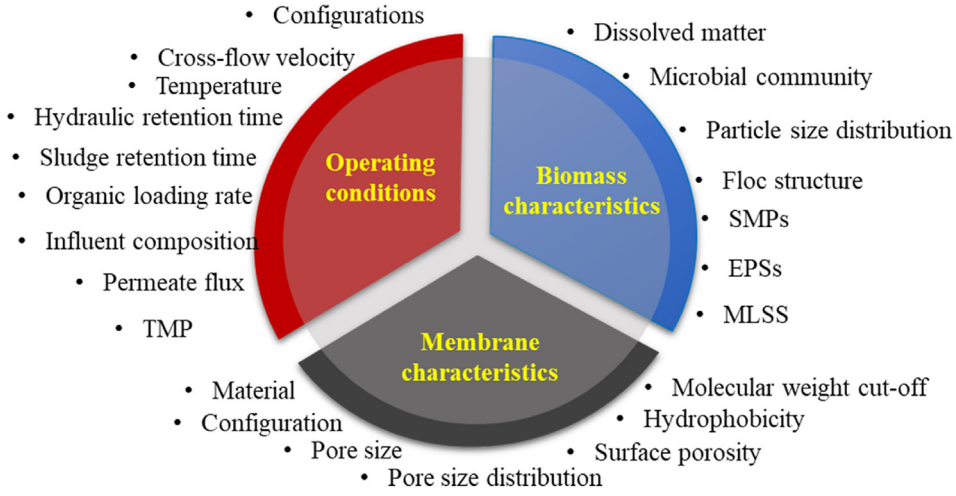


Fig. 5. Membrane fouling: controlling parameters.

methane production (50%) remained in dissolved form in liquid phase at 15 °C (Smith et al., 2013). The dissolved methane in permeate accounts for 25–67% of the total methane depending on the temperature from 15 to 25 °C (Smith et al., 2012). Several strategies have been reported to recover dissolved methane e.g. stripping of AnMBR effluent through post-treatment aeration, degassing membrane reactor, and down-flow hanging sponge reactor (Crone et al., 2016; McCarty et al., 2011; Shin et al., 2016b). The most feasible approach to recover methane from liquid phase is bubbling with air or another gas by using bubble column reactor. In another approach, there is a direct contact between liquid and gas phases in the hollow fiber membrane contactor in which methane diffused from liquid phase to gas phase. In this process more than 72% methane is recovered for power generation (Crone et al., 2016; Shin et al., 2016b). Based on the considerable potential for dissolved methane, future researches are needed to evaluate trade-off between recovery efficiency and operation cost.

4. Strategies to control membrane fouling and system performance

Fig. 5 presents key bottlenecks controlling membrane fouling in AnMBRs. Membrane fouling can either be controlled by optimizing the operating conditions or surface modifications of membrane or developing membranes less prone to fouling or controlling biomass properties.

4.1. Optimization of operational conditions

Viscosity of liquid decreases with increase in temperature; leading to improve flux through membrane. To obtain same shear stress, a lower shear rate will be enough for low viscosity sludge and hence demands lower energy (Dereli et al., 2012). Methanogenic activity is significantly controlled by temperature change. Different experimental studies revealed that methanogenic activity reduced at lower temperature (15 °C) as compared to higher temperature (25 °C) (Ho and Sung, 2009; Hu and Stuckey, 2007; Jain, 2018; Khanal, 2008; Zhao et al., 2018). From economical point of view, AnMBR is to be treated at ambient temperature. In AnMBR for biogas production, OLR ranges from 0.23 to 33.7 kgCOD m^{-3} d^{-1} (Chen et al., 2016). More biogas production is achieved by increasing organic loading rate. Wijekoon et al. (2011) reported that biogas production rate was proportional to organic loading rate. When organic loading rate was increased from 5 to 12 kgCOD m^{-3} d^{-1} then biogas production rate also increased from 5 to 35 L d^{-1} in two stage thermophilic AnMBR. Higher the OLR, higher will be activity of methanogens that increase the biogas production. Disadvantage of increasing OLR is accumulation of VFA that requires irreversible acidification and will deteriorate biogas production (Wijekoon et al., 2011).

HRT plays a vital role in the performance of AnMBR. Depending on feed characteristics, system hydraulics, and sludge properties etc., HRT values can be changed from as low as 1 h to as high as 30 d (Chen et al., 2016; Jeong et al., 2010; Stuckey, 2012). Ho and Sung (2009) highlighted the effect of HRT on methane recovery by reducing HRT from 12 to 6 h. The methane production from municipal wastewater decreased by 13% as result of increasing VFA accumulation in AnMBR (Ho and Sung, 2009). In contrast, Gao et al. (2014) observed an increase in methane production by lowering HRT from 8 to 6 h, which might be connected to increasing OLR. There could be an optimized value of HRT for each case depending on feed characteristics, system hydraulics, reactor design and substrate types etc. (Gao et al., 2014). Disadvantage of shorter HRT may lead to membrane fouling, VFA accumulation and reduction of biogas production (Dereli et al., 2014a,b).

The key parameter that plays a vital role in performance of AnMBR is upflow velocity that has two opposing effects on biological removal efficiency. A better mixing of substrate-biomass may be achieved by increasing upflow velocity. On the other hand, disadvantage of increasing upflow velocity may come in form of detachment of captured solids due to high hydraulic shear force and damage removal efficiency by increasing settling velocity. The effect of upflow velocity and permeability increased with increase in upflow velocity (Ozgun et al., 2015). However, some studies contradicted that upflow velocity provided strong shear impact, which broke up sludge aggregate into fine particles in mixed liquor and enhance amounts of microbial byproducts, leading to more fouling (Berube et al., 2006).

4.2. Membrane characteristics

The other principal factor that affects membrane fouling is the membrane characteristics that include morphology, materials, pore size, zeta potential, and hydrophobicity/hydrophilicity affinity (Kochkodan and Hilal, 2015). The modification of membrane surface is done to increase hydrophilic character of surface by altering the physical or chemical interactions with membrane surface (Meng et al., 2017). It was reported that interaction between membrane surface and sludge foulants remarkably was affected more by surface roughness and zeta potential than membrane hydrophilicity/hydrophobicity. Membrane fouling was lower as membrane surface had higher zeta potential and certain roughness (Kochkodan and Hilal, 2015).

Nominal pore size of membrane has also significant effect on permeate flux. It is clear that membrane pore size is function of

microbial mixed liquor being treated. There is higher rate of fouling for large membrane pore size as compared to small pore size. Generally, AnMBR uses membrane pore sizes of 0.02–0.5 μm (Ozgun et al., 2013). Hollow fibers can be inserted in submerged AnMBRs (Kim et al., 2011; Liu et al., 2013; Yoo et al., 2012). Nevertheless, flat sheets have been examined due to high stability, easy to clean and exchange (Lin et al., 2011). Tubular membranes can also be used due to low fouling tendency associated with well-defined hydrodynamic conditions on membrane surface compared to hollow-fiber membrane (Calderón et al., 2011). On the other hand, tubular membrane requires high energy input because it operates at high pressure for filtration as it is applied as side-stream of AnMBR (Stuckey, 2012). On the basis of material, membranes can be divided into three types as: polymer, metallic and ceramic (inorganic). The advantage of using polymeric membranes in AnMBR is of lower cost as compared to others (Stuckey, 2012). The disadvantages of polymer membrane are lower permeability and reduced stability towards chemical cleaning than ceramic membrane.

4.3. Biomass characteristics

Permeate flux has been significantly affected by concentration of suspended solids in mixed liquor. More accumulation of colloids, sludge particles, macromolecular matter, and microbial products in bioreactors was observed at higher mixed liquor suspended solids (MLSS). Higher sludge viscosity will reduce lower rise velocity of larger biogas bubbles, thereby lowering the effect of gas bubbling on membrane fouling control and fiber movements in AnMBRs (Deng et al., 2016). Permeate flux is affected by sludge floc size. Large flocs might be pulled away from membrane by high inertial force and high shear induced diffusion as well as low Brownian diffusion. More porous and permeable cake layer formed with larger and loosely deposited flocs, thus reduced fouling resistance (Skouteris et al., 2012). Microbial by-products such as SMP and EPS had strongest engagement with membrane fouling when compared to other sludge characteristics such as MLSS, floc size, particle size distribution etc (Lin et al., 2014). High Brownian diffusion and permeation drag might be occurred due to retention and adsorption of SMP and EPS on or into membrane (Deng et al., 2016; Meng et al., 2017). Thus, this will cause membrane pore blocking by gel formation and seep into pores and spaces of cake layer. Gel layer clutched more SMP/EPS as compared to cake layer and thus had more filtration resistance than cake layer. These effects directed negative impact on permeate flowrate by membrane fouling. Moreover, pretreatment reduced inorganic precipitation on ceramic membrane in AnMBR (Aslam et al., 2015; Gao et al., 2013; Hong et al., 2014; Lin et al., 2013).

4.4. Membrane scouring strategies

Membrane fouling is controlled by applying shear stress through different approaches such as biogas sparging, particle sparging, and rotating/vibrating membrane. Biogas sparging is commonly used for controlling membrane fouling in AnMBRs. Xie et al. (2014) observed that fouling rate decreased and flux increased by increasing sparging rate. Mitigation of membrane fouling in vibrating AnMBR occurs with different motions/mechanical forces i.e., longitudinally, transversely or their combination that produces the shear effect at membrane surface (Bilad et al., 2012; Eliseus et al., 2018; Kola et al., 2014). In particle sparging, AnMBR also called anaerobic fluidized membrane bioreactor (AFMBR) used granular activated carbon (GAC) with recycling of liquid instead of biogas sparging to control membrane fouling (Ahmad et al., 2018; Aslam et al., 2019, 2014; Kim et al., 2011; Shoener et al., 2016). Fluidized GAC as scouring agent provided scouring (mechanical) action on membrane surface and also provided large surface area for biofilm growth. It had low energy consumption and was highly effective to control membrane fouling (Aslam et al., 2017a; Charfi et al., 2018a, 2017a; Gao et al., 2014; Ng et al., 2014; Zhang et al., 2017). AnMBRs with rotating flat sheet, tubular, hollow fiber or helical membrane modules have been examined (Jiang et al., 2013; Wu et al., 2008). Fouling can be controlled by increasing rotation speed. Jiang et al. (2013) stated that fouling rate in rotating flat sheet MBR was lower as compared to conventional MBRs when consuming same energy. This technique was granted to improve membrane fouling control by increasing shear action with rotation (Ruigómez et al., 2017).

4.5. Filtration cycles

Filtration cycles technique consisted of filtration and relaxation with optional backwashing. Relaxation, duration of time with no permeation, is broadly applied for membrane fouling control. Membrane fouling is also controlled by backwashing in which reverse flow of permeate remove foulants on membrane surface. Backwashing is typically significant for cleaning of accumulated particles over membrane surface, which mainly causes reversible fouling; disentangle loosely adherent aggregates sludge from surface of membrane (Ozgun et al., 2013). Some studies revealed that backwashing could be effective for removing not only external fouling but also pore clogging. Moreover, biogas combined with backwashing can sufficiently control internal fouling. It was also reported that pore blocking was not fully reversible by backwashing and partially leads to irreversible fouling (Lei et al., 2018).

4.6. Chemical cleanings

Membrane fouling controls by chemical cleaning remains a headache during wastewater treatment in AnMBRs. This way of combating fouling increases membrane replacement cost, decreases system productivity and reduces membrane lifespan. However, membrane performance can be restored by chemical cleaning. Membrane permeability is improved periodically through maintenance cleaning (MC). On the other hand, recovery cleaning (RC) is used to recover membrane permeability (Bagheri and Mirbagheri, 2018; Meng et al., 2017; Wang et al., 2014). Chemical cleaning may include acids, bases, oxidants, surfactants and chelates. Acids cleaning can be used to remove precipitated inorganic matters and mineralization that exert between biopolymer and salts (Malaeb et al., 2013b; Wang et al., 2014). Organic foulants can be removed by using bases such as sodium hydroxide (Bagheri and Mirbagheri, 2018). Oxidants are also used to clean organic and biological foulants through oxidation and disinfection (Meng et al., 2017). The rhamnolipids are also used as chemical cleaning reagents against membrane fouling. These agents do not face problem of high cost, low solubility, and toxicity (Kim et al., 2015b).

4.7. Comparison of different fouling control strategies

There are different pathways through which membrane fouling can be controlled to some extent and in some methods could be removed to maximum extent. Such strategies have advantages and drawbacks in different aspects while treating different types of wastewaters in AnMBRs. The filtration resistance resulted by concentration polarization and cake formation could be mitigated through higher cross flow velocity (Skouteris et al., 2012). However, cost related to higher cross flow velocities and formation of fine/colloid particles at high velocity is a major concern. So high shear force has negative impact on membrane permeate flux in AnMBR. Ultrasonic irradiation is another path to control membrane fouling. But it becomes unfeasible at high sludge concentration that requires more ultrasonic irradiation energy for long period of time (Meng et al., 2017). In addition, high power density and low frequency are required to improve the cleaning efficiency. Biogas sparging rate can determine process efficiency as membrane fouling decreases by increasing sparging rate (Stuckey, 2012). It is an efficient technique; however, energy expenditure is high. Relaxation and

backflushing are two widely employed hydraulic cleaning protocols. Mechanical cleaning by combining biogas sparging and particles/carriers, vibration and rotation has also positive effect on membrane fouling control. Adding carriers/particles provide solid support for biomass growth and causes reduction in floc rupture (Vyrides and Stuckey, 2009). It provides sufficient shear force on membrane surface by mechanical cleaning and reduces TMP and membrane fouling. However, the possible damage of membrane surface should be taken into consideration. Physical cleaning is used only to remove cake layer and reversible fouling (temporary fouling) (Lin et al., 2013). It is a fast process as compared to chemical cleaning and produces no chemical waste. This cleaning process does not involve membrane degradation. In contrast, chemical cleaning is used to remove organic, inorganic, and irreversible fouling by using different chemical cleaning agents such as bases, acids and oxidants (Lin et al., 2013). But these chemicals may be corrosive or caustic and can damage membrane. The combination of chemical and physical cleaning is a powerful strategy to enhance cleaning efficiency, for example, chemical-enhanced backwash (CEB) and ultrasound assisted chemical cleaning are two applicable ways. Moreover, particle sparging through bulk liquid recirculation is a promising technology to mitigate cake layer formation and control membrane filtration resistance (Aslam et al., 2017a). However, novel cleaning strategies and configurations should be paid attention. Their pilot-scale and full-scale feasibility should be further verified. Novel chemical foam cleaning, self-cleaning membrane development and bioelectrochemical cleaning are also worth investigating.

5. Novel configurations

5.1. Anaerobic fluidized-bed membrane bioreactor

Recently biogas sparging was combined with biofilm carriers or fluidized media to reduce biogas flow rates for fouling reduction as shown in Fig. 6a (Vyrides and Stuckey, 2009). However, energy consumption was still higher because gas sparging accounts for largest fraction of energy requirement. AFMBR is a newly developed novel liquid recirculation particle-sparging system that coupled with membrane filtration without biogas sparging as shown in Fig. 6b (Kim et al., 2011). Good mass transfer characteristics with high concentration of active microbial species indicate singularity of this process on other processes. Membrane fouling in this configuration was controlled through scouring action of GAC, also known as fluidized media, on membrane surface (Aslam and Kim, 2019). This process has low energy demand (Aslam et al., 2017b, 2018c; Charfi et al., 2018b). The maximum methane recovery from wastewater treatment is also acquired by two staged system. Low-strength wastewater was investigated by Kim et al. (2011) in coupled system of anaerobic fluidized bioreactor (AFBR) and AFMBR for methane rebate. The generation of methane from this system was 4.11 mol$CH_4 m^{-3}$. The composition of this methane was 86% at less than 5 h HRT. Total energy required for fluidization obtained from only 30% gaseous methane which indicated AFMBR as more propitious bioenergy production technology (Kim et al., 2011). Same favorable points for AFMBR system were also derived from study of Yoo et al. (2012) and Aslam et al. (2018a,b) as it was highly efficient, had low energy demand, and ability of large bioenergy production.

Another simplified and smaller footprint system was reported by Gao et al. (2014) which consisted of integrated anaerobic fluidized bed membrane bioreactor (IAFMBR). According to this study, 80 ± 2% methane content acquired in biogas production and conversion of influent COD to methane was about 50% in which 25% of produced methane went to liquid phase. Shin et al. (2014) reported that enriched acetoclastic culture grew rapidly on GAC as compared to acetoclastic methanogenic activity (SAMA). Due to this reason, further research should deal with growth of syntrophic acetogens (VFA-degrading) and acetoclastic methanogens on GAC for maximum biogas production. Recently, Seib et al. (2016) developed a new configuration of anaerobic cross-flow particle sparging MBR using GAC as fluidized media as presented in Fig. 6c (Seib et al., 2016). Another study investigated glass beads as fluidized media (Düppenbecker et al., 2017). The fluidized media in cross-flow system provided 55–120% longer membrane operation between cleanings under reduced cross-flow velocity (CFV), resulting in 98–99% reduced energy requirements than that of conventional tubular membrane operational techniques under higher cross-flow velocities of 3–5 m/s (Seib et al., 2016).

5.2. Anaerobic submerged rotating membrane bioreactor (AnSRMBR)

Membrane fouling can be controlled by many attempts such as chemical/physical cleanings to applications of scouring media fluidization and transverse vibration (Kola et al., 2014; Wu et al., 2017). This issue can be overcome by using novel configuration, which consists of submerged rotating membrane bioreactor as shown in Fig. 6d (Ruigómez et al., 2017; Wu et al., 2008). In this technique, immersed and rotatable membrane is fixed on axis and rotatory movement occurs through electric motor. This strategy has improved filtration capacity and fouling prevention ability. Mainly cross flow velocity is produced by rotation of membrane module. A rotary filtration system is an economically feasible technique than conventional cross flow systems. Another advantage of this technique is its antifouling action proposed by rotating membrane that increases shear action between membrane and floating media (Kim et al., 2014). This system has large permeate flux in ultrafiltration and provides strong shear impact that results in reduce cake on membrane surface (Jørgensen et al., 2014).

5.3. Anaerobic dynamic membrane bioreactor (AnDMBR)

Problems in conventional AnMBR processes include high cost of membrane configuration, low membrane flux, and rapid membrane fouling that can be overcome by using dynamic membrane (DM) technology. In an AnDMBR, supported cake layer configuration is used for solid-liquid separation. Materials for supporting are meshes and fabrics with macropores (Ersahin et al., 2014). This technology of DM commutes major problem of membrane fouling into advantage. After complete fouling of dynamic membrane, cake layer removal and cleaning can occur through easy way and can be replaced with new deposited layer. By this way, membrane cost is reduced. Chemical resistance of fillers and dynamic membrane material are helpful in selection of cleaning process and its frequency (Ersahin et al., 2012; Ma et al., 2013). A large pore size mesh of 200 μm was used by Alibardi et al. (2014) in lab-scale anaerobic dynamic MBR. They reported the effect of variation in COD removal and HRT on changing in biogas production and methane content that was 1.0 L/d maximum and 50–79% respectively. Sustainable aspect of AnDMBR occurs by low CFV (due to large pore size) that had low energy input and improved methanogenic activity by reducing shear stress on biomass. Maximum amount of biogas was produced due to higher methanogenic activities of cake layer (Alibardi et al., 2014). Application of dynamic membrane on monofilament woven support was also investigated by Ersahin et al. (2014). They observed different average production of methane at 20 and 40 days SRTs which was 0.31 ± 0.02 $LCH_4/gCOD_{removed}$ and 0.34 ± 0.04 $LCH_4/gCOD_{removed}$, respectively. In the study of Xie et al. (2014), Dacron mesh of pore size 40 μm was used and achieved methane production of 0.34 $LCH_4/gCOD_{removed}$.

5.4. Anaerobic electrochemical membrane bioreactor (AnEMBR)

Recently, development of multifunctional conductive, catalytic, porous, hollow-fiber cathodes (CCPHF) in anaerobic electrochemical membrane bioreactor (AnEMBR) has gained promising attention and presented in Fig. 6e (Katuri et al., 2018, 2014; Werner et al., 2016). Katuri et al. (2014) recommended a novel configuration of a microbial electrolysis cell (MEC) with anaerobic filtration that incorporated

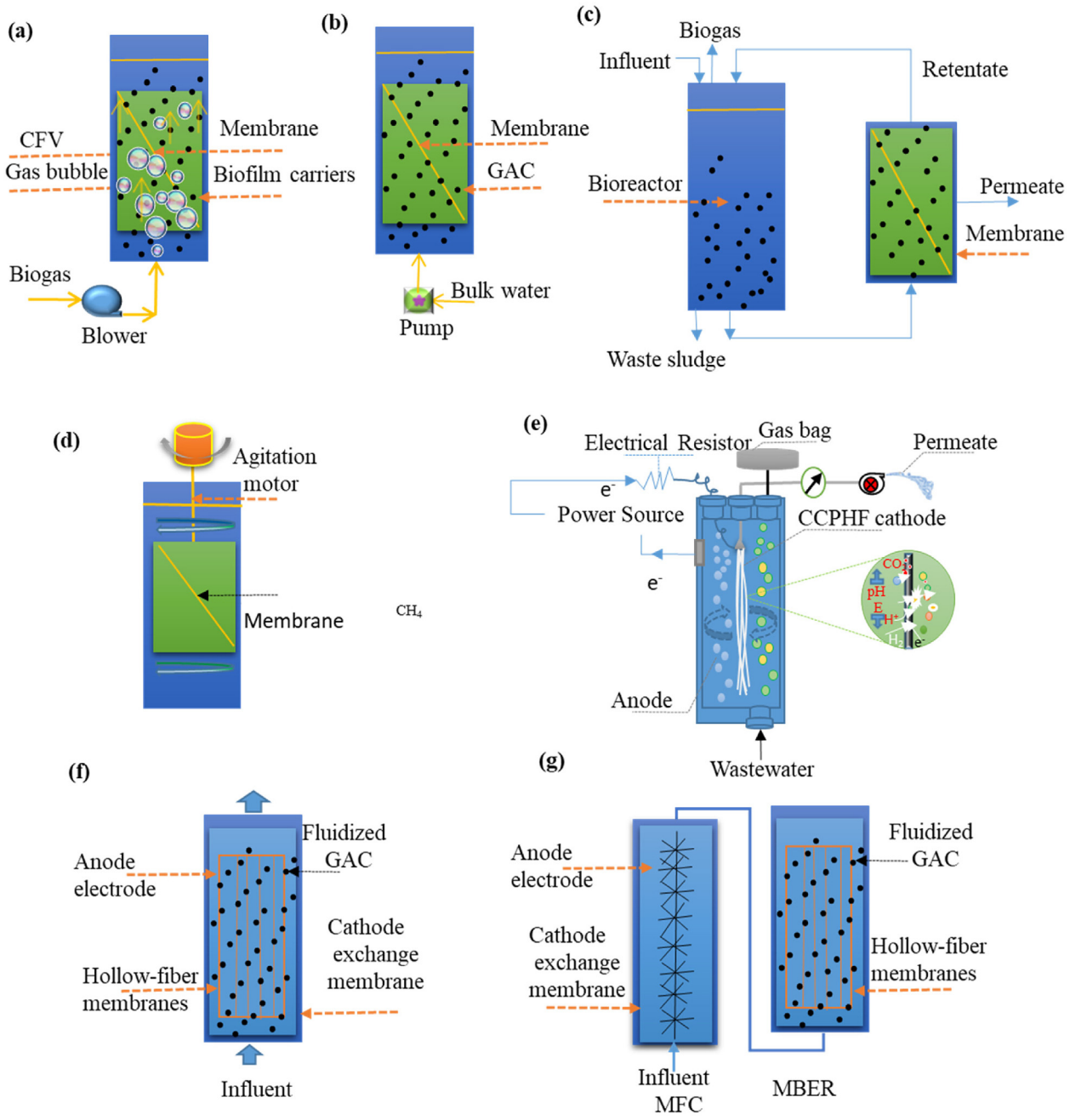


Fig. 6. Different configurations of AnMBR (a) Biogas-particle sparging; (b) Liquid recirculation particle-sparging; (c) Anaerobic cross flow-particle sparging MBR; (d) Anaerobic rotating MBR (e) Anaerobic electrochemical membrane bioreactor; (f) Individual fluidized MBER; (g) Hybrid MFC-MBER system.

porous, conductive, nickel-based hollow fiber membranes (Ni-HFM). The benefit of Ni-based porous conductive membrane was recovery of energy and treated water in single stage. The problem of low specific surface area of cathode was also defeated by increasing packing density of cathode (Katuri et al., 2014). The other problem in this technology was membrane fouling. Therefore to become more attractive and advantageous choice for low organic strength wastewater treatment, efficiency of energy recovery and fouling are to be under consideration. The hydrogen evolution rate increased as applied voltage was increased. As rate of gas bubble formation was increased at membrane surface, the scouring action was enhanced, resulting in lower membrane fouling (Ding et al., 2018).

Membrane fouling in bioelectrochemical system also reduces by using fluidized bed membrane bioelectrochemical reactor (MBER) in which GAC is used as scouring media as shown in Fig. 6f (Cusick et al., 2014; Li et al., 2014, 2016). GAC reduced TMP and its work as anode was minor. When this system coupled with regular microbial fuel cell (MFC), energy recovery and contaminants removal occurred mostly in MFC section. Fluidized media aided in removing inorganic scaling on cathode surface (Cusick et al., 2014). Different studies have investigated the system of MFCs coupled with AnMBRs to improve effluent quality as shown in Fig. 6g (Li et al., 2014, 2016; Ren et al., 2014; Tian et al., 2014; Wang et al., 2013). Malaeb et al. (2013a,b) examined a hybrid system of MFC-MBER that consolidated with ultrafiltration, flat-sheet, conductive bio-cathode membrane. This porous bio-cathode membrane provided benefits of filtration for effluent and cathode for reduction reaction (Malaeb et al., 2013a; Logan, 2010; Rabaey and Rozendal, 2010). Wang et al. (2011) reported new technology of bioreactor namely, anaerobic membrane bioelectrochemical reactor in which membrane worked as cathode and filter media in MFC. The

advantage of this process was high effluent quality and large bioenergy production. The membrane fouling would be minimized due to anode oxidation of substrates that has low organic loading during membrane filtration (Wang et al., 2011).

5.5. Anaerobic osmotic membrane bioreactors (AnOMBRs)

AnOMBR is a new configuration for wastewater treatment integrating forward osmosis (FO) and anaerobic treatment. FO membrane allows water to pass through semi-permeable membrane from feed solution having lower osmotic pressure to draw solution with higher osmotic pressure in AnOMBR (Chen et al., 2016; Gu et al., 2015). This process does not require any energy input to run filtration process in comparison to traditional pressure AnMBRs. Gu et al. (2015) treated low strength wastewater treatment in AnOMBR for recovering of energy in form of biogas at mesophilic temperature. A significant amount of methane was achieved in the range of 0.25–0.3 $LCH_4/gCOD_{Removed}$ (Gu et al., 2015). Chen et al. (2014) investigated methane recovery ability of FO-AnMBR system and found that methane of 0.21 $LCH_4/gCOD_{Removed}$ produced with 65–78% methane content. Though, the yield of methane was 58% of theoretical yield due to dissolved methane in effluent and low methanogenic activity under salinity environment (Chen et al., 2014). Therefore, future research is needed to investigate the activity of methanogens and microbial kinetics to enhance biogas generation under salinity conditions.

5.6. Anaerobic membrane distillation bioreactors (AnMDBRs)

Bioreactors that engaged with membrane distillation process operate at thermal difference phenomenon. Membrane is characterized as hydrophobic and microporous in process in which water vapors pass through membrane to form water on other side (Goh et al., 2015; Kim et al., 2015a). Coupling of anaerobic process with membrane distillation (MD) can be used as competitive technology for methane production as mesophilic or thermophilic operation (Kim et al., 2015a). Spare biogas can be employed for heating purpose and energy applications (Goh et al., 2015). Methane gas remains exist in gas phase in AnMDBR and easier to extract and recover (Chen et al., 2016). Therefore, permeate obtains from AnMDBR has lower dissolved methane than from other AnMBRs (Goh et al., 2015). Xie et al. (2014) demonstrated that biogas produced in hybrid anaerobic MBR-MD system with 58–72% contents of methane while no fraction of methane obtained from MD process (Xie et al., 2014). AnMDBRs overcome other systems in terms of small footprints, complete retention of organics and biomass for efficient conversion of organics into biogas (Goh et al., 2015; Kim et al., 2015a). AnMDBR has also strength for complete deletion of total phosphorous to control eutrophication (Kim et al., 2015a). However, further study is still needed with respect to biogas generation and challenges associated with AnMDBRs.

6. Energy demand and recovery in AnMBRs

The overall energy balance analysis was purposed by two aspects: energy that was obtained from methane production and energy consumption during operation of AnMBRs. Energy independency ratio is the ratio of measured energy potential to total energy demand (Mei et al., 2016). Major part of energy in AnMBRs is consumed in fouling control in membrane tanks which is more than 70% of energy consumption of AnMBRs (Lin et al., 2013; Pretel et al., 2014; Smith et al., 2014). The energy that is used in fouling control mainly depends on fouling mitigation method applied.

6.1. Energy demand

Total energy demands in AnMBRs mainly consider two aspects: energy requirement in fouling control and others. The energy demand in others includes energy requirements for the rest of AnMBR systems including operation of reactor; permeate pumps, and biogas/liquid circulation in AnMBRs (Shin and Bae, 2018). Energy requirements associated with membrane operation in AnMBRs consists of two operations: permeate pumping and fouling control. Membranes are immersed in submerged AnMBRs and gas is introduced below membrane module in form of biogas. The other configuration consists of membrane module in outside bioreactor in side stream pumped cross flow system and mixed liquor is forced through pump to membrane module and recycled back to bioreactor. This system is operated at constant pressure with pump and performs two operations: liquid cross flow and driving force for permeation. Energy required for permeate flow can be obtained theoretically. Energy demands for fouling control can be further subdivided into two parts in systems: energy for pumping in cross flow and energy for biogas sparging in submerged configurations (Martin et al., 2011). Energy demands in submerged AnMBRs were calculated from 0.038 to 5.68 $kW\,h\,m^{-3}$. While in side stream AnMBRs, energy demand was observed from 3 to 7.3 $kW\,h\,m^{-3}$ due to cross flow velocity and bioreactor MLSS on flux and pressure losses (Liao et al., 2006; Martin et al., 2011). As strength of wastewater increases from 0.24 to 10 $gCOD\,L^{-1}$, energy obtained from biogas also increases ranges from 0.62 to 34.8 $kW\,h\,m^{-3}$ (Martin et al., 2011). Energy demands in different configurations are summarized in Table 1.

6.2. Energy recovery

Biogas produced from AnMBR has usually composition of: 50–90% methane, 3–15% carbon dioxide, and 0–15% nitrogen (Lin et al., 2013). Methane rich biogas may have demand in digester heating, electricity generation, or recycle for fuel generation. It was investigated that 2.02 $kW\,h/kgCOD_{Removed}$ obtained in AnMBR treating synthetic wastewater (Lin et al., 2013). Methane production is significantly affected by temperature variation. Methane production increases as temperature increases due to high specific growth and consumption rates of substrate (Lei et al., 2018; Lin et al., 2013). Anaerobic rotating membrane bioreactor has energy potential of 0.92 $kW\,h/m^3$ packed with hollow fiber membrane (Lei et al., 2018; Shin and Bae, 2018). Methane production in anaerobic bioreactor with submerged forward osmosis membrane recorded as 0.21 $LCH_4/gCOD$ (Chen et al., 2014). Moreover, Methane production in upflow anaerobic sludge blanket (UASB) reactor

Table 1
Energy consumption with different configurations.

AnMBR configuration	Energy consumption ($kW\,h/m^3$)	References
Cross flow AnMBR	3–7.3	(Aslam et al. (2017a); Liao et al. (2006))
Particle-sparging cross flow AnMBR	0.05–0.3	(Düppenbecker et al. (2017); Seib et al. (2016))
Biogas-sparging submerged AnMBR	0.038–5.68	(Martin et al. (2011); Shin and Bae (2018))
Biogas particle-sparging submerged AnMBR	0.15–1.0	(Aslam et al. (2017a))
Liquid circulation particle–sparging submerged AnMBR	0.0087–0.23	(Aslam et al. (2018c); Kim et al. (2011); Shin et al. (2014))
Anaerobic submerged rotating MBR	0.23	(Shin and Bae (2018))
Anaerobic oelectrochemical membrane bioreactor (AnEMBR)	0.27	(Katuri et al. (2014))
Hybrid MFC-MBER system	0.0186–0.09	(Li et al. (2014); Li et al. (2016); Ren et al. (2014))

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Table 2
Summary of methane production and system performance of AnMBRs.

Scale	Wastewater	configuration	Reactor capacity (L)	Membrane characteristics	Temperature (°C)	HRT (h)	Influent COD (mg/L)	Methane yield (LCH_4/$gCOD_{Removed}$)	Methane content/ conversion rate	COD removal (%)	Reference
Pilot	Synthetic molasses wastewater	External	72	Silver coated PVDF, PES 0.22 μm	35–37	30	2400	0.31	70–75%	82	(Amouamouha and Gholikandi (2018))
Lab	Synthetic municipal wastewater	Submerged	6	FS PVDF 0.20μ m	25	8	670 ± 100	0.326	93	–	(Chen et al. (2017b); Chen et al. (2017c))
Lab	Synthetic food wastewater	Submerged	21.6	FS 0.4 μm	35 ± 1	20–120 d	3000–27000	5–50 L/d	49–67%	94 ± 8	(Casu et al. (2012))
Lab	Synthetic wastewater	Submerged	4	FS, CTA 0.025 m^2	25	15–40	460	–	65–78%	96%	(Chen et al. (2014))
lab	Synthetic municipal wastewater	External	4	HF, PVDF 0.22 μm	20 ± 0.5	12	330–370	0.16 ± 0.006	45.3%	91.9 ± 1.5	(Chen et al. (2017a))
Lab	Pulping whitewater landfill leachate	Submerged	10	FS, PVDF 70 kDa	37	–	2.78–3.35	–	68%	90	(Gao et al. (2010))
Lab	Synthetic wastewater	Submerged	7.4	FS	35.7	10 d	20,100	2.4 L/d	–	99.5	(Ersahin et al. (2017))
Lab	Synthetic municipal wastewater	submerged	6	FS, PVC 0.2 μm	25 ± 1	12	492 ± 112	0.30	86.9	97.07	(Nie et al. (2017b))
Lab	Food waste	External	15	HF, PTFE 0.2 μm	–	5–30 d	73610 ± 3100	–	58–61	80.4–92.9	(Cheng et al. (2018))
Pilot	Municipal wastewater	External submerged	310	HFM 0.045 μm	6–30	10–13.4	892 ± 271	0.235	67.1		(Gouveia et al. (2015))
Lab	Food wastewater	Submerged	5	HF 0.04 μm	24 ± 2	24	1463	2.8 ± 0.2 L/d	38.4	87.50	(Galib et al. (2016))
Pilot	Domestic wastewater	External	50	UF 100 kDa	37	15–60	685	30 L/d	70%	55–90	(Saddoud et al. (2007))
Lab	Synthetic municipal solid waste	Submerged	3	FS, PE 0.4 μm	35	0.37–5.7	4000–26000	–	1–71%	93–94.5	(Trzcinski and Stuckey (2009))
Lab	Domestic wastewater	Submerged	3.6	FS, Ceramic 0.2 μm	25–30	7.5	330.4 ± 89.8	0.3 ± 0.001	85.70%	–	(Yue et al. (2015))
Lab	Sewage	Submerged	6	FS, PE 0.2 μm	20–25	6–48	492 ± 112	2.11–2.85 L/day	32–77	80–97	(Nie et al. (2017a))
Lab	Synthetic wastewater	External	0.7 + 0.06	FS	20–24	0.25–5.7	900	0–0.2	–	greater than 89	(Alibardi et al. (2016))

FS: Flat Sheet, HF: Hollow fiber, CTA: Cellulose triacetate, Lab: Laboratory scale, PE: Polyethylene, PES: Polyethylene sulfone, PET: Polyethylene terephthalate, PTFE: Polytetrafluoroethylene, PVC: Polyvinylchloride, PVDF: Polyvinyledene fluoride, UF: Ultrafiltration.

was observed in ranges from 0.16 to 0.2 LCH_4/gCOD (Chen et al., 2014). Energy production from municipal organic waste treated through anaerobic fermentation process was recorded as 4.54 kW h/kgCOD (Chen et al., 2017d). Methane generation potential in AnDMBR was reported in range from 0.28 to 0.31 $LCH_4/gCOD_{Removed}$ (Ersahin et al., 2016). Anammox-AnMBR produced methane of 0.223 $LCH_4/gCOD_{Removed}$ (Chen et al., 2016). AnOMBR was found to have methane production potential ranges from 0.25 to 0.3 $LCH_4/gCOD_{Removed}$ (Chen et al., 2016). Table 2 summarizes the methane production and system performance of different AnMBRs.

Energy potential in AnMBRs for wastewater treatment is mainly affected by influent sulfate concentration (Li et al., 2015). Energy potential in biogas sparging AnMBRs recorded from 0.08 to 0.50 $kWhm^{-3}$ and 0.14 $kWhm^{-3}$ for particle sparging bioreactor (Lei et al., 2018; Shin and Bae, 2018). Energy production in MBER was recorded about 0.011 $kWhm^{-3}$. The coupled MFC plus MBER system recovered total energy of 0.047 $kWhm^{-3}$ (Li et al., 2014). It was also observed that in AFMBRs with bulk liquid recirculation, energy requirement was sufficiently low than energy produced from methane as 0.23 kW h m^{-3} (Aslam et al., 2017b). Energy potential can be increased by using staged AFMBR for treatment of effluents generated by AFBR. Net energy produced from this system was investigated about 0.238 kW h m^{-3}. This was 9.8 times more than energy required to operate AFMBR system (Aslam et al., 2018c). Here methane can be recovered as biogas or dissolved in effluent. The highest methane yield observed ranges from 0.29 to 0.33 LCH_4/gCOD when treating low strength wastewater (Hu and Stuckey, 2007). Lowest methane yield also reported as 0.12 and 0.08–0.09 LCH_4/gCOD when operated at 11–25 °C and 25–30 °C, respectively (Chu et al., 2005). These values indicate significance of temperature in production and recovery of biogas. The energy production potential is significantly affected by influent COD concentrations and SO_4^{2-}-S particularly for low-strength wastewater having COD lower than 300 mg/L (Li et al., 2015). Recently, seven pilot scale AnMBRs were found to be energy positive or energy neutral, suggesting that AnMBRs not only accomplish electrical energy balance but also achieve energy output (Lei et al., 2018).

6.3. Strategies to reduce energy expenditures

Energy consumption and related cost are both connected to membrane fouling issues. The major focusing points in energy reduction are associated with module configuration, control systems, low energy membrane cleaning methods, or other fouling control methods such as membrane vibration, scouring agent with granular medium, electric field, and others (Meng et al., 2017; Krzeminski et al., 2017). The major aspects that correspond to energy reduction are: combined effect of number of membrane modules, interval of filtration and relaxation/backwash, use of flux enhancer, pump configuration and recirculation rate (Krzeminski et al., 2017). Moreover, operating condition that is lower than critical flux is successive turn to achieve hydraulic and energy efficiency. As membrane flux has direct link to the hydraulic utilization of membrane, so it plays a positive effect in energy efficient system. An energy efficient system in the form of increasing filtration at high flux in limited/short time interval is also suggested. In another approach, intermittent electric field is also used as fouling control for energy saving purpose (Meng et al., 2017).

As aforementioned, energy consumption in AnMBRs can be minimized by implementation of higher membrane flux. This target can be achieved by using high permeable membrane and introducing periodic chemical cleanings. Aslam et al. (2017b) compared flux rate of two different configured AnMBRs with particle sparging. Hydrophilic ceramic membrane inserted in first reactor with periodic MCs. The other one had hydrophobic polyvinylidenefluoride (PVDF) without MCs. Results declared that flux rate was 1.7 times higher (17 L m^{-2} h^{-1}) with ceramic membrane than polymeric membranes (Aslam et al., 2017b). The selection of optimal MLSS conditions can also reduce energy expenditure. This is done by maintaining concentration of MLSS at low level in membrane tank. It causes reduction of specific gas demand (SGD_m). Robles et al. (2012) showed that as MLSS concentration increased from 23 to 28 g L^{-1}, SGD_m also increased from 0.25 to 0.5 N m^3 m^{-2} h^{-1} at critical flux of 14 L m^{-2} h^{-1} in anaerobic gas sparging hollow fiber membrane bioreactor. Pretel et al. (2015) reported the path of usage of primary clarifier to reduce MLSS concentration from 10–18 to 5–10 g L^{-1} in membrane tank. Low MLSS concentration requires low energy demand in AnMBRs but will be engaged with increase in sludge production (Pretel et al., 2015; Robles et al., 2012; Shin and Bae, 2018). Therefore, more explanatory and detail work is required on this approach. The implementation of coagulant or fluidizing GAC can also reduce energy consumption. The drawback of particle sparging AnMBR is to reduce lifespan of membrane by scouring action of particles on membrane surface and need for replacement of membrane (Shin et al., 2016a). The use of coagulant as $FeCl_3$ also caused replacement of membrane twice for 536 days where TMP increased with enhancement of operating flux and resulted in irreversible fouling (Dong et al., 2015). Further research is needed as frequent replacement of membrane increases economic aspects.

7. Future perspectives

Over last decade, many researchers have focused on applying new and novel technologies to mitigate membrane fouling and improve performance of AnMBRs. Optimized operational conditions and biomass characteristics, cell entrapment, antifouling membranes, biological concepts, fluidized media and electrically based strategies are promising to reduce membrane fouling and to enhance energy sustainability. The practicality of these technologies on the larger scale needs to be assessed to identify further research requirements. Current practices to prevent cake layer formation over the membrane surface involve biogas sparging with carriers, liquid recirculation with particle sparging while pore blockage is avoided by chemical cleaning. Furthermore, membrane fouling can be reduced by using biomass entrapment technology that has low SMP/EPS in mixed liquor and large particle size of sludge (Juntawang et al., 2017). Application of antifouling membranes could be another way to mitigate fouling. In-situ cleaning of membrane surface by the pretreatment of feed with suitable coagulants/adsorbents and particle sparging is also recommended. However, sustainability in fouling mitigation and energy recovery can be achieved by integrating several approaches to get an optimal control of foulants.

Dissolved methane recovery in AnMBRs is another issue that offset their economics in terms of energy neutrality or positivity. The recovery of dissolved CH_4 is strongly associated with the overall treatment cost of wastewater using AnMBR. Hence, it is strongly desired to develop a methane recovery method that enables economical methane recovery at minimum cost. To overcome the disadvantages of mechanical and chemical cleaning, biological methods are also introduced. These methods improve the effluent quality as well as biogas production. Many researchers are trying in the development of multifunctional CCPHF that is more efficient in recovery of resources from wastewater. Fabrication of CCPHF with ceramic membrane could be an alternative route because these membranes have high chemical, thermal, and mechanical stability.

AnMBRs outperform in several applications to treat domestic and industrial wastewaters under extreme operating conditions. An optimal solution to address issues of membrane fouling, inefficient dissolved methane recovery, poor nutrients removal, and removal of undesired compounds can be realized by using novel AnMBR configurations. Biological approaches, such as quorum quenching, need to be explored for effective and energy efficient fouling mitigation in AnMBRs. Furthermore, the following important constraints must be addressed for further improvements to comply the reliability and commercial status of AnMBR technology:

- Operational optimization for minimizing energy consumption
- Energy positivity and/or energy neutrality to achieve significant market volumes by improving energy production potential
- Improvements in the membrane configurations using sole design optimization aiming to the efficient control of AnMBR performance.
- To explore the new cost-effective mineral based composite membranes with variety of improved intrinsic characteristics to withstand particle sparging and cleaning protocols.

8. Conclusions

AnMBR performance is greatly influenced by temperature, pH, HRT and others parameters. It is promising due to energy saving, high COD removal, methane production, and low sludge yield. However, there are also some challenging aspects in the form of fouling and its association with energy expenditures, dissolved methane recovery, sulfide, pH and alkalinity, ammonia and long chain fatty acids. Different new configurations have been developed to make this strategy more energy-efficient and can enhance to commercial level. Control of membrane fouling and dissolved methane recovery play an important role to make AnMBRs technology an energy efficient system and require further study.

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