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Utilization of aerobic granulation to mitigate membrane fouling in MBRs

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Abstract. Membrane bioreactor (MBR) is a compact and efficient wastewater treatment and reclamation technology; but, it is limited by membrane fouling. The control of membrane fouling significantly increases operational and maintenance costs. Bacteria and their byproducts - extracellular polymeric substances (EPS) - are major contributors to membrane fouling in MBRs. A recent attempt at fouling mitigation is the development of aerobic granular sludge membrane bioreactor (AGMBR) through the integration of a novel biotechnology - aerobic granulation - and MBR. This paper provides an overview on the development of AGMBR to mitigate membrane fouling caused by bacteria and EPS. In AGMBR, EPS are used up in granule formation; and, the rigid structure of granules provides a surface for bacteria to attach to rather than the membrane surface. Preliminary research on AGMBR using synthetic wastewater show remarkable membrane fouling reduction compared to conventional MBR, thus improved membrane filtration. Enhanced performance in AGMBR using actual municipal wastewater at pilot-scale has also been reported. Therefore, further research is needed to determine AGMBR optimal operational conditions to enhance granule stability in long-term operations and in full-scale applications.

Keywords: aerobic granulation; AGMBR; membrane bioreactor (MBR); membrane fouling; wastewater treatment

1. Introduction

Current wastewater treatment technologies such as conventional activated sludge (CAS) struggle to meet regulatory discharge requirements in terms of water quality. These systems fail to remove nutrients (nitrogen and phosphorus) to acceptable levels (Baeza *et al.* 2004, Oleszkiewicz and Barnard 2006). The presence of nutrients in water bodies results in excessive growth of aquatic plants (eutrophication) which leads to the deterioration of surface water quality (Smith *et al.* 1999). Eutrophication causes increased biomass of phytoplankton and macrophyte vegetation, growth of benthic and epiphytic algae, increased blooms of gelatinous zooplankton (marine environment), loss of commercial and sport fisheries, increased toxins from bloom-forming algal

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species, reduced carbon available to food webs, increased taste and odor problems, reduced species diversity, increased treatment costs prior to human use, and decreased aesthetic value of the water body (Smith and Schindler 2009, Badruzzaman *et al.* 2012). In addition, CAS produces large volumes of sludge that need further stabilization for safe disposal. The handling of sludge significantly increases operational costs.

Membrane bioreactor (MBR) has emerged as a technology of choice for wastewater treatment over the conventional systems (Le-Clech *et al.* 2006, Meng *et al.* 2009, Drews 2010, Lin *et al.* 2012). An MBR is a hybrid of biological treatment and physical liquid-solids separation by membrane filtration (Chang *et al.* 2002, WEF 2011). MBRs have been successfully used for the treatment and reclamation of both municipal and industrial wastewaters (Brindle and Stephenson 1996, van Dijk and Roncken 1997, Ueda and Hata 1999, Chu *et al.* 2006, Mutamim *et al.* 2012, Friha *et al.* 2014). The technology offers the following advantages over CAS: high-quality effluent, higher volumetric loading rates, shorter hydraulic retention time (HRT), longer solids retention time (SRT), less sludge production, and potential for simultaneous nitrification/denitrification in long SRTs (Judd 2008, WEF 2011, Mutamim *et al.* 2013, Metcalf & Eddy Inc. 2014). The inclusion of membranes in the system eliminates the need for secondary clarifiers. This elimination of secondary clarifiers and shorter HRTs results in significantly reduced footprint. In addition, the prolonged acclimatization of microorganisms due to the long SRTs in MBRs is suitable for the removal of recalcitrants.

However, the major drawback of MBR is membrane fouling (Kimura *et al.* 2005, Meng *et al.* 2009, Lin *et al.* 2014, Vanysacker *et al.* 2014). Membrane fouling is the deposition of particles on the membrane surface or inside its pores resulting in reduced membrane permeability. The decline in permeability reduces membrane performance and membrane lifespan (Chang *et al.* 2002). Common membrane fouling mitigation strategies in MBRs include air scouring, operational relaxation and backflushing, chemical backwashing or modification of membrane surface chemistry. These strategies significantly increase MBR operating and maintenance costs (Chang *et al.* 2002). Bacteria and their byproducts - extracellular polymeric substances (EPS) - have been identified as major contributors to membrane fouling in MBRs (Chang and Lee 1998, Meng *et al.* 2009, Lin *et al.* 2014). EPS are bacterial byproducts originating from microbial metabolites, cell lysis, or unmetabolized wastewater components (Drews 2010). EPS are known to significantly affect the physico-chemical properties of microbial aggregates such as surface charge, hydrophobicity, settling properties, flocculation, adsorption ability, etc (Sheng *et al.* 2010, Show *et al.* 2012). EPS primarily comprise proteins, polysaccharides (carbohydrates), humic acids, nucleic acids, lipids and uronic acids (Ng *et al.* 2010, Pan *et al.* 2010, Lin *et al.* 2014). It is generally accepted that proteins and polysaccharides are the major components of EPS (Liu and Fang 2003, Drews 2010, Sheng *et al.* 2010, Lin *et al.* 2014); and, they are the components typically measured as an indication of the amount of EPS. EPS are sub-divided into two, namely bound EPS and soluble EPS (also referred to as soluble microbial products - SMPs) (Lin *et al.* 2014). Bound EPS are further split into loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) (Liu *et al.* 2010). SMPs and bound EPS are considered the major foulants in MBRs (Chang and Lee 1998, Jang *et al.* 2006, Meng *et al.* 2009, Wang *et al.* 2014) as they have multiple interactions with all other foulants (Lin *et al.* 2014). The aggregation of biomass happens by the participation of bound EPS and SMPs, which provide a highly hydrated gel matrix (Chang *et al.* 2002, Jang *et al.* 2006). The hydrated gel matrix acts as a ‘glue’ to keep the microbial aggregates together. The ‘glue’ property of EPS is the main cause of membrane fouling.

By virtue of their significance in fouling, current research is focused on coupling a novel biotechnology, aerobic granulation, with MBR to mitigate membrane fouling due to bacteria and EPS (Li *et al.* 2005, Tay *et al.* 2007, Tu *et al.* 2010, Juang *et al.* 2011, Thanh *et al.* 2013). Research in this direction is gradually developing the aerobic granular sludge membrane bioreactor (AGMBR). AGMBR offers a unique advantage of utilizing EPS for granule formation; and once formed, the granules provide a surface for bacteria to attach to rather than the membrane surface. The large size and rigid structure of the granules is expected to play a key role in membrane fouling mitigation. This paper provides an overview of the development of AGMBR and identifies areas for further research.

2. Membrane fouling in MBR

Membrane fouling can be classified into three: biofouling, organic fouling, and inorganic fouling (Spettmann *et al.* 2007). Biofouling refers to the attachment, growth and metabolism of bacteria or flocs on the membrane (Meng *et al.* 2009). Membrane biofouling is a two-step process, starting with early bacterial attachment, followed by multiplication of bacteria on the membrane surface to form a cluster of cells (Vanysacker *et al.* 2014). It has been indicated that membrane biofouling is one of the most important operational problems in membrane based systems (Guo *et al.* 2012); as such, its control is a key research area in MBRs.

Organic fouling, on the other hand, is the deposition on the membrane of biopolymers, e.g., polysaccharides and proteins, in the MBR mixed liquor. The biopolymers are found in EPS. It has been reported that biopolymers have significant impact on membrane fouling in MBRs (Wang and Li 2008). EPS play significant roles in membrane fouling through blocking of membrane pores, adherence to the membrane surface, affecting the cake structure and inducing osmotic effect (Lin *et al.* 2014). In addition to EPS, research has indicated that MBR sludge also contains a pool of large-sized free organic solutes called biopolymer clusters (BPC) (Lin *et al.* 2009). BPCs result from the clustering of loose EPS and SMPs in the sludge cake (Wang *et al.* 2011). The large membrane surface in an MBR provides a conducive environment for BPC formation and growth; and, the formation and accumulation of BPCs in MBR causes serious membrane fouling (Sun *et al.* 2011).

Inorganic fouling is due to the precipitation of inorganic substances onto the membrane surface or in the membrane pores. Examples of inorganic species responsible for inorganic fouling in MBRs include: Ca^{2+}, Mg^{2+}, Fe^{3+}, Al^{3+}, SO_4^{2-}, PO_4^{3-}, CO_3^{2-}, OH^-, etc (Wang *et al.* 2008, Wang *et al.* 2014). These species precipitate due to hydrolysis which leads to pH change, and oxidation (Guo *et al.* 2012). Essentially, inorganic fouling is produced from the chemical precipitation of inorganic species and/or biological precipitation of inorganic-organic complexes (Wang *et al.* 2014). Inorganic fouling is also termed ‘mineral scale’ in order to differentiate it from biofouling and organic fouling (Shirazi *et al.* 2010). Crystallization and particulate fouling are the two key mechanisms that play critical roles during inorganic fouling in MBR. In crystallization, precipitation of ions is the pathway to deposition on the membrane surface; while, particulate fouling is the deposition following convective transportation of colloidal particulate matter in the solution to the membrane surface (Lee and Lee 2000).

Of the three classes of membrane fouling in MBRs, biofouling and organic fouling are the most significant (Jang *et al.* 2006, Wang and Li 2008, Meng *et al.* 2009, Lin *et al.* 2014). This implies that bacteria and EPS are the major biological contributors to membrane fouling in MBRs.

3. Aerobic granulation

Aerobic granulation is a novel biotechnology which was developed in the late 1990s (Beun *et al.* 1999, Tay *et al.* 2001, Moy *et al.* 2002) with potential application for the treatment of both municipal and industrial wastewaters. Aerobic granules are aggregates of microorganisms that form through microbe-to-microbe self-immobilization without any medium (Adav *et al.* 2008). These granules are dense microbial consortia packed with different microbial species and typically contain millions of organisms per gram of biomass that can collectively biodegrade wastewater pollutants (Liu and Tay 2004, Tay *et al.* 2009). Compared to CAS, aerobic granules exhibit excellent settling properties, strong microbial structure, high biomass retention, high resilience to toxic chemicals, and good ability to handle high organic and shock loading rates (Liu and Tay 2004, Tay *et al.* 2009, Show *et al.* 2012). This technology can also substantially reduce sludge generation, land space requirements and post-treatment operational costs.

Since EPS act as construction materials for microbial aggregates by providing the highly hydrated gel matrix (Chang *et al.* 2002, Jang *et al.* 2006), they act as adhesives in the agglomeration of bacteria to form granules (Zhu *et al.* 2012). Essentially, EPS help to initiate the aerobic granulation process by bringing the bacterial cells and other particulate matter into an aggregate (Liu *et al.* 2004, Lee *et al.* 2010). Thus, they play a significant role in maintaining the structural integrity of granular sludge (Tay *et al.* 2001, McSwain *et al.* 2005). This implies that since EPS are utilized in granules formation, there would be less EPS concentration in solution to cause fouling.

The application of aerobic granulation is perceived as one of the most promising wastewater treatment technologies in this century. The application of aerobic granulation also holds promise beyond the limits of municipal wastewater treatment into areas such as the treatment of high-strength organic wastewater (Moy *et al.* 2002, Tay *et al.* 2004), bioremediation of toxic aromatic pollutants (Jiang *et al.* 2002, Nancharaiah *et al.* 2006, Adav *et al.* 2007), removal of nitrogen and phosphorus (Lemaire *et al.* 2008, Yilmaz *et al.* 2008), sulfate and nuclear waste (Khan *et al.* 2013), and biosorption of heavy metals (Liu *et al.* 2002, Liu *et al.* 2003, Sun *et al.* 2008).

3.1 Characteristics of aerobic granules

Granule stability is associated with physical, chemical and biological characteristics of the granular sludge. These attributes make the granular sludge process unique. Physical attributes include parameters such as morphology, settleability, density and strength. Chemical attributes are indicated by specific oxygen utilization rate (SOUR) and cell surface hydrophobicity. Biological attributes have microbial structure and diversity. These are briefly discussed below.

3.1.1 Physical attributes

Morphology

Unlike conventional floccular sludge, aerobic granules have a defined spatial shape. The shape of the granules is nearly spherical with a very clear outline (Peng *et al.* 1999, Tay *et al.* 2001, Zhu and Wilderer 2003). The average roundness in terms of aspect ratio is higher than 0.6 for aerobic granules grown on different carbon sources (Tay *et al.* 2009). The roundness of aerobic granules is mainly influenced by hydrodynamic shear force which erodes the irregularities in the granule surface, making it smooth and round. The average diameter of aerobic granules lies in the range of 1.0 to 5.0 mm (Liu *et al.* 2003, Ergüder and Demirer 2005, Li *et al.* 2009, Show *et al.* 2012). This mean diameter of mature aerobic granules is a function of several factors including substrate composition, organic loading rate, shear force, etc.

Settleability

Settleability is a key operational factor that determines the efficiency of liquid-solids separation in biological wastewater treatment processes (Adav *et al.* 2008). Settling velocity and sludge volume index (SVI) are used to describe sludge settleability. The formation of granules significantly improves sludge settleability, offering desirable biomass retention in the reactor as well as enhancing organic degradation efficiency and reactor stability. The settling velocity of aerobic granules is associated with granule size and structure; and, it varies from 25-70 m/h which is significantly higher than activated sludge flocs (7-10 m/h) (Liu *et al.* 2003, Qin *et al.* 2004, Adav *et al.* 2008). The SVI of aerobic granules is in the range 40-100 mL/g (Peng *et al.* 1999, Jiang *et al.* 2002, Tay *et al.* 2002, Toh *et al.* 2003). These values are significantly lower than activated sludge with SVI values above 200 ml/g (Liu *et al.* 2003). This indicates a much better settleability.

Granule density and strength

Small-sized granules tend to be denser than large-sized granules (Toh *et al.* 2003, Yang *et al.* 2004). The specific gravity of aerobic granules typically ranges from 1.004 to 1.065 (Tay *et al.* 2009). Granules with high physical strength are capable of withstanding high abrasion and shear (Show *et al.* 2012). The physical strength of granules is expressed as integrity coefficient (%); and, it is defined as the ratio of residual granules to the total weight of the granular sludge after 5 minutes of shaking at 200 rpm on a platform shaker (Tay *et al.* 2009). It has been reported that the integrity coefficient is greater than 95% for aerobic granules grown on glucose and acetate (Tay *et al.* 2002).

3.1.2 Chemical attributes

Specific oxygen utilization rate (SOUR)

The microbial activity of microorganisms is measured using the specific oxygen utilization rate (SOUR). A very wide range of SOUR values for aerobic granules have been reported in the literature: 34-168 mg O_2/g. volatile suspended solids (VSS).h (Morgenroth *et al.* 1997, Tay *et al.* 2001, Yang *et al.* 2003, Zhu and Wilderer 2003). It has been indicated that the SOUR of aerobic granules increases with increasing shear force (Tay *et al.* 2001). It has also been shown that increased shear force allows for significant stimulation of respiration activities of aerobic microorganisms (Tay *et al.* 2001).

Cell surface hydrophobicity

Cell surface hydrophobicity is an important affinity force in cell self-immobilization and attachment processes (Kos *et al.* 2003). The hydrophobicity of aerobic granules is reported to be two-fold higher than normal activated sludge bioflocs (Liu *et al.* 2004). The cell surface hydrophobicity for acetate-fed aerobic granules has been reported in the literature as 73%, and glucose-fed aerobic granules was 68% (Tay *et al.* 2009). It has been indicated that the cell surface hydrophobicity plays a crucial role in cell-to-surface attachment and cell-to-cell self-immobilization (Del Re *et al.* 2000, Liu and Tay 2002, Tay *et al.* 2002).

3.1.3 Biological attributes

Microbial structure

Confocal laser-scanning microscopy (CLSM) has been used for studying the microstructure of aerobic granules (Tay *et al.* 2002, Tay *et al.* 2002, Tay *et al.* 2003, Toh *et al.* 2003). The co-existence of various bacterial consortia has been reported. The obligate aerobic ammonium-oxidizing bacterium *Nitrosomonas spp.* was found mainly at depth of 70-100 μm from the granule surface, and aerobic granules contained channels and pores that penetrated to a depth of 900 μm below the granule surface (Tay *et al.* 2009). The anaerobic bacterium *Bacteroides spp.* was also identified at a depth of 800-900 μm from the granule surface (Tay *et al.* 2002), while a layer of dead microbial cells was located at a depth of 800 to 1000 μm (Toh *et al.* 2003). This structure is suitable for simultaneous removal of organics and nutrients. However, aerobic granules with smaller diameter will be more effective for wastewater treatment as these granules have more live cells within a given volume of granules.

Microbial diversity

The microbial diversity of aerobic granules is related to the composition of the culture media from which they are cultivated (Tay *et al.* 2009) and the structure of the granules (Show *et al.* 2012). Numerous species of bacteria have been identified in aerobic granules by different researchers. Nitrifying, denitrifying, heterotrophic, glycogen-accumulating, and phosphorus accumulating bacteria have been identified in aerobic granules developed under different conditions (Lin *et al.* 2003, Meyer *et al.* 2003, Tsuneda *et al.* 2003, Yang *et al.* 2003). Oxidizing bacteria mainly dominate the granule surface, while anaerobes and dead cells were detected at the granule center (Tay *et al.* 2002, Lee *et al.* 2010). The presence of anaerobic bacteria in aerobic granules is likely to result in the production of organic acids and gases within the granules (Show *et al.* 2012). These end products of anaerobic metabolism can destroy the granules or at least diminish their long-term stability. Therefore, further research is needed to determine the optimum size of granules and how to maintain granule size for long-term stability without disintegration.

3.2 Current challenges of aerobic granulation

Despite the numerous benefits aerobic granular sludge offer, majority of research studies worldwide on aerobic granulation have been conducted mainly in the laboratory sequential batch reactors (SBRs) with synthetic wastewaters (Show *et al.* 2012, Khan *et al.* 2013) with only a few using actual wastewater (Cassidy and Belia 2005, Liu *et al.* 2010, Pronk *et al.* 2015). The major shortcoming impeding the industrial application of this technology is the long-term system operational instability and granule disintegration problems (Show *et al.* 2012). Deterioration in granule stability over time impacts the efficiency of wastewater treatment and is a major issue affecting the effectiveness of aerobic granulation in full-scale operations. Aerobic granules have been observed to disintegrate after prolonged operation (Tay *et al*. 2001, Jiang *et al*. 2002, Moy *et al*. 2002, Tay *et al*. 2002, Liu and Tay 2004, Adav *et al*. 2007, Adav *et al*. 2008, Show *et al*. 2012). Hypotheses proposed to account for stability deterioration include growth of a filamentous population (Liu and Liu 2006, Li and Wang 2008) and anaerobic degradation within granules (Zheng *et al*. 2006, Adav *et al*. 2009). Hence, ensuring long-term adequate structural integrity of aerobic granules is currently one of the major challenges hindering the practical application of the aerobic granulation process.

4. Aerobic granular sludge membrane bioreactor

Recent research has focused on coupling aerobic granulation with MBR as a mitigation strategy for membrane biofouling and organic fouling. The AGMBR technology is novel in its integration of two innovations in wastewater treatment: aerobic granulation and membrane filtration technologies. In AGMBR, aerobic granules biodegrade the pollutants; and, membrane filtration is employed to separate the treated effluent from aerobic granules resulting in a high-quality effluent free of particulates. In this way, AGMBR combines the unique advantages offered by the two technologies. Enhanced pollutant removal is expected in AGMBR due to the rich microbial morphology and diverse microbial species of granular sludge. The potential for nutrients (nitrogen and phosphorus) removal also exists in the evolving AGMBR. Aerobic granules have a layered structure with an oxic zone near the granule surface, a transient anoxic zone, and anaerobic zone at the granule center (Yilmaz *et al*. 2008). This layered structure is suitable for simultaneous organics, nitrogen, and phosphorus removal. Additionally, the agglomeration of different species of bacteria in aerobic granules and their resilience to toxicity offer a great opportunity to degrade emerging contaminants such as pharmaceuticals and personal care products. As such, AGMBR produces reclaimed water of high quality in a compact set-up.

In terms of membrane fouling, the large size and structural rigidity of aerobic granules expectedly reduces pore blocking and cake layer formation. EPS are also used up in aerobic granule formation, hence less soluble EPS (SMPs) in the mixed liquor to accelerate membrane fouling. The schematic diagrams of AGMBR in typical granular sludge column-type reactor and conventional MBR reactor are presented in Figs. 1 and 2, respectively. Preliminary results on the AGMBR technology so far are outlined below.

4.1 Performance of AGMBR

The first research on AGMBR found that membrane permeability was more than 50% higher in

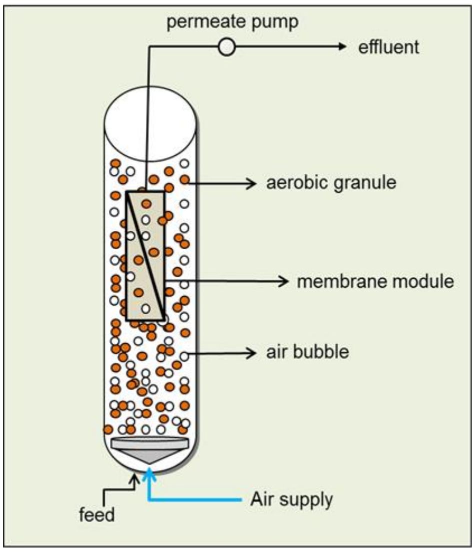

Fig. 1 Schematic diagram of AGMBR in a typical granular sludge columnar reactor

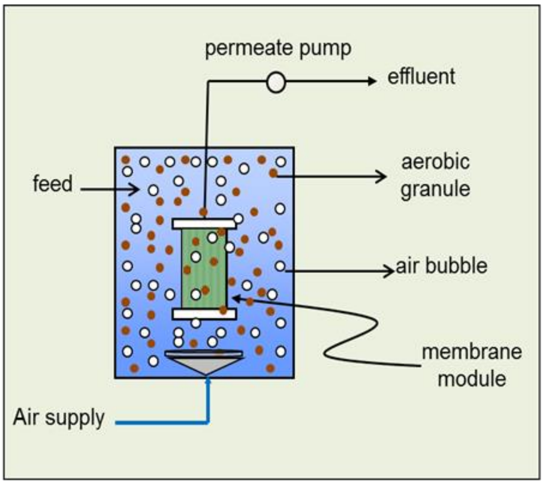

Fig. 2 Schematic diagram of AGMBR in a conventional MBR reactor

AGMBR compared to conventional MBR (Li *et al.* 2005). Tay *et al.* (2007) compared AGMBR and submerged MBR in a 4-month bench-scale study using synthetic wastewater. While treatment efficiency was similar for the two systems, the granular sludge in AGMBR promoted much better filtration with membrane permeability loss being twice as low as that of the submerged MBR (Tay *et al.* 2007). It has been indicated that the EPS in AGMBR is largely bound to the cells, hence low concentration of EPS in the supernatant to cause fouling (Yu *et al.* 2009). Membrane fouling in AGMBR treating high-strength wastewater at different organic loading rates (OLRs) has also been investigated (Thanh *et al.* 2008). Results from this study showed that fouling was only due to soluble polysaccharides (sPS) in the AGMBR supernatant. This indicates that a portion of EPS - bound EPS - adhered to the granular surface rather than membrane surface.

In addition to improved membrane performance in AGMBR, one study reported higher removal efficiency of pollutants (Tu *et al.* 2010). Membrane fouling rate in this study was maintained below 0.1 kPa/day at an operational mixed liquor suspended solids (MLSS) above 18,000 mg/L. Other reported AGMBR performances include stable operation at 20 L/m^2.h for 61 days with much better performance than MBR (Wang *et al*. 2013), extension of filtration period by 78 days without physical cleaning in AGMBR (Thanh *et al*. 2013), and significant fouling control with 99% organics removal (Vijayalayan *et al.* 2014).

Research on AGMBR in continuous flow operation on actual wastewater has also been reported. Sajjad *et al*. (2016) studied membrane performance in a pilot-scale continuous flow AGMBR using actual municipal wastewater for 220 days. The authors reported 8-fold lower membrane fouling in AGMBR compared to conventional MBR. The significant fouling mitigation is attributable to the high protein to polysaccharides (PN/PS) ratio of 3.3 of the EPS, about 4-fold lower SMP, and large size of the granules in the AGMBR system (Sajjad *et al.* 2016).

The performances of AGMBR, as reported by different researchers, are presented in Table 1.

4.2 Stability of aerobic granules in AGMBR and further research areas

It may appear that the integration of aerobic granulation with MBR would impact the granule characteristics. In this regard, a few studies have been conducted to investigate the stability of

Table 1 Reported performance of AGMBR

Medium	Key findings	Reference
Synthetic wastewater (300±150 mg COD/L)	▪ membrane permeability was > 50% higher than MBR ▪ COD removal efficiency was 80 - 95%	(Li *et al.* 2005)
Synthetic wastewater (2000 mg COD/L)	▪ enhanced filtration characteristics of AGMBR mixed liquor due to low compressibility of its biomass ▪ at constant TMP, when TMP increased 8-fold, membrane permeability loss in AGMBR was 1.68-fold lower than in MBR ▪ at constant flux testing, when flux increased 3-fold, membrane permeability loss in AGMBR was 21-fold lower than in MBR ▪ COD removal efficiency was 99%	(Tay *et al.* 2007)
Synthetic wastewater (2000 mg COD/L)	▪ lower TMP in AGMBR than in MBR; and, the low TMP was sustainable for long-term operation ▪ AGMBR showed better filterability ▪ secreted EPS were mostly bound to the cells hence, hence low concentration in the liquor to cause membrane fouling ▪ COD removal efficiency was > 85%	(Yu *et al.* 2009)
Synthetic wastewater (500 mg COD/L)	▪ improved membrane performance in AGMBR (fouling rate continuously below 0.1 kPa/day at MLSS > 18,000 mg/L) ▪ COD removal efficiency was 93.8 - 98.4% ▪ sludge settleability and morphology positively impacted membrane performance ▪ aerobic granules formation increased the protein to polysaccharides ratio (PN/PS) of EPS and SMPs ▪ increased (PN/PS) resulted in higher relative hydrophobicity and zeta potential of the sludge, as well as increased mixed liquor filterability	(Tu *et al.* 2010)
Synthetic wastewater (819.20 mg/L of CH_3COONa)	▪ stable operation at a flux of 20 $L/m^2.h$ for 61 days with much better performance than MBR ▪ aerobic granules in the AGMBR were stable throughout the experimental duration (61 days)	(Wang *et al.* 2013)
Synthetic wastewater (700 mg COD/L)	▪ extension of filtration duration up to 78 days with no physical cleaning (slow rate of fouling at 0.027 kPa/day) ▪ organics (TOC) removal efficiency was 94% ▪ total nitrogen (TN) removal efficiency was 59% (1.76 mg TN/g VSS h) at OLR of 0.86 kg $TOC/m^3.day$	(Thanh *et al.* 2013)
Synthetic wastewater (1260 mg COD/L)	▪ membrane fouling rate was 0.105 kPa/day at steady state ▪ the system achieved 99% and 61% removal for organic carbon and nitrogen, respectively (with a 35% of denitrification) ▪ granule breakage resulted in rapid fouling in the membrane	(Vijayalayan *et al.* 2014)
Actual wastewater (300±25 mg COD/L)	▪ membrane fouling rate (TMP rise) was about 8 times lower in AGMBR than MBR with flocculent sludge ▪ high PN/PS ratio (3.30) of the EPS (~ 4-fold low SMPs), high particle size and sludge settleability were the main contributing factors to membrane fouling mitigation ▪ high PN/PS ratio in the granules allowed for increase in filtration flux	(Sajjad *et al.* 2016)

intrinsic characteristics of aerobic granules in AGMBR. Findings from these studies show that aerobic granules in an AGMBR system possess outstanding degradation ability despite having a relatively smaller diameter (average of 2.00 mm) compared to granules from an SBR (average of 3.00 mm) (Li *et al*. 2007, Li *et al*. 2008). The changes in granule characteristics have been attributed to the overgrowth of filamentous bacteria. The relatively smaller granule size in AGMBR system may reduce the long-term deterioration of the granule as the anaerobic core may be smaller.

In general, research findings to-date show a strong potential of AGMBR to offer a sustainable and innovative wastewater treatment and reclamation solution. However, the following research areas require further investigation in order to implement AGMBR at the full-scale:

- Production of granules with long-term structural stability.
- Investigation of nutrients (nitrogen and phosphorus) removal in AGMBR. Alternating anaerobic - aerobic conditions are suitable conditions for the removal of nutrients. Aerobic granules exhibit a layered structure which offers these favorable conditions.
- Testing the AGMBR at the pilot-scale to establish optimum operating conditions for simultaneous organics, nitrogen and phosphorus removal. This will be invaluable to obtaining detailed AGMBR plant design information.

5. Conclusions

MBR technology has emerged as a technology of choice for wastewater treatment and reclamation. However, membrane fouling is the major drawback impeding the wider application of the MBR technology. Coupling aerobic granulation with MBR is aimed at overcoming this challenge. Aerobic granule formation in AGMBR can mitigate membrane fouling, thus, prolong membrane lifespan and ultimately reduce operational and maintenance costs. Preliminary results on AGMBR indicate effective membrane fouling mitigation and improved permeate flux which will translate to an elongation of membrane lifespan resulting in lower operating and maintenance costs. AGMBR also shows enhanced organics and nitrogen removal whilst maintaining the stability of intrinsic granules characteristics. Further research is, therefore, required to determine AGMBR optimal operational conditions to enhance granule stability in long-term operations and in full-scale applications using actual wastewater.

References

Adav, S.S., Lee, D.J. and Lai, J.Y. (2009), “Proteolytic activity in stored aerobic granular sludge and structural integrity”, *Bioresour. Technol.*, **100**(1), 68-73.

Adav, S.S., Lee, D.J. and Ren, N.Q. (2007), “Biodegradation of pyridine using aerobic granules in the presence of phenol”, *Water Res.*, **41**(13), 2903-2910.

Adav, S.S., Lee, D.J., Show, K.Y. and Tay, J.H. (2008), “Aerobic granular sludge: Recent advances”, *Biotechnol. Adv*., **26**(5), 411-423.

Adav, S.S., Lee, D.J. and Tay, J.H. (2008), “Extracellular polymeric substances and structural stability of aerobic granule”, *Water Res*., **42**(6-7), 1644-1650.

Adav, S.S., Lee, D.J. and Tay, J.H. (2007), “Activity and structure of stored aerobic granules”, *Environ. Technol.*, **28**(11), 1227-1235.

Badruzzaman, M., Pinzon, J., Oppenheimer, J. and Jacangelo, J. G. (2012), “Sources of nutrients impacting surface waters in Florida: A review", *J. Environ. Manage.*, **109**, 80-92.

Baeza, J.A., Gabriel, D. and Lafuente, J. (2004), "Effect of internal recycle on the nitrogen removal efficiency of an anaerobic/anoxic/oxic (A2/O) wastewater treatment plant (WWTP)", *Proc. Biochem.*, **39**(11), 1615-1624.

Beun, J.J., Hendriks, A., van Loosdrecht, M.C.M., Morgenroth, E., Wilderer, P.A. and Heijnen, J.J. (1999), "Aerobic granulation in a sequencing batch reactor", *Water Res.*, **33**(10), 2283-2290.

Brindle, K. and Stephenson, T. (1996), "The application of membrane biological reactors for the treatment of wastewaters", *Biotechnol. Bioeng.*, **49**(6), 601-610.

Cassidy, D.P. and Belia, E. (2005), "Nitrogen and phosphorus removal from an abattoir wastewater in a SBR with aerobic granular sludge", *Water Res.*, **39**(19), 4817-4823.

Chang, I.S. and Lee, C.H. (1998), "Membrane filtration characteristics in membrane-coupled activated sludge system-the effect of physiological states of activated sludge on membrane fouling", *Desalination*, **120**(3), 221-233.

Chang, I., Le Clech, P., Jefferson, B. and Judd, S. (2002), "Membrane fouling in membrane bioreactors for wastewater treatment", *J. Environ. Eng.*, **128**(11), 1018-1029.

Chu, L., Zhang, X., Yang, F. and Li, X. (2006), "Treatment of domestic wastewater by using a microaerobic membrane bioreactor", *Desalination*, **189**(1-3), 181-192.

Del Re, B., Sgorbati, B., Miglioli, M. and Palenzona, D. (2000), "Adhesion, autoaggregation and hydrophobicity of 13 strains of Bifidobacterium longum", *Lett. Appl. Microbiol.*, **31**(6), 438-442.

Drews, A. (2010), "Membrane fouling in membrane bioreactors - Characterisation, contradictions, cause and cures", *J. Membr. Sci.*, **363**(1-2), 1-28.

Ergüder, T.H. and Demirer, G.N. (2005), "Investigation of granulation of a mixture of suspended anaerobic and aerobic cultures under alternating anaerobic/microaerobic/aerobic conditions", *Proc. Biochem.*, **40**(12), 3732-3741.

Friha, I., Karray, F., Feki, F., Jlaiel, L. and Sayadi, S. (2014), "Treatment of cosmetic industry wastewater by submerged MBR with consideration of microbial community dynamics", *Int. Biodeterior. Biodegrad.*, **88**, 125-133.

Guo, W., Ngo, H.H. and Li, J. (2012), "A mini-review on membrane fouling", *Bioresour. Technol.*, **122**, 27-34.

Jang, N., Shon, H., Ren, X., Vigneswaran, S. and Kim, I.S. (2006), "Characteristics of bio-foulants in the membrane bioreactor", *Desalination*, **200**(1-3), 201-202.

Jiang, H.L., Tay, J.H. and Tay, S.T.L. (2002), "Aggregation of immobilized activated sludge cells into aerobically grown microbial granules for the aerobic biodegradation of phenol", *Lett. Appl. Microbiol.*, **35**(5), 439-445.

Juang, Y.C., Su, A., Fang, L.H., Lee, D.J. and Lai, J.Y. (2011), "Fouling with aerobic granule membrane bioreactor", *Water Sci. Technol.*, **64**(9), 1870-1875.

Judd, S. (2008), "The status of membrane bioreactor technology", *Trends Biotechnol.*, **26**(2), 109-116.

Khan, M.Z., Mondal, P.K. and Sabir, S. (2013), "Aerobic granulation for wastewater bioremediation: A review", *Canadian J. Chem. Eng.*, **91**(6), 1045-1058.

Kimura, K., Yamato, N., Yamamura, H. and Watanabe, Y. (2005), "Membrane fouling in pilot-scale membrane bioreactors (MBRs) treating municipal wastewater", *Environ. Sci. Technol.*, **39**(16), 6293-6299.

Kos, B., Šušković, J., Vuković, S., Šimpraga, M., Frece, J. and Matošić, S. (2003), "Adhesion and aggregation ability of probiotic strain Lactobacillus acidophilus M92", *J. Appl. Microbiol.*, **94**(6), 981-987.

Le-Clech, P., Chen, V. and Fane, T.A.G. (2006), "Fouling in membrane bioreactors used in wastewater treatment", *J. Membr. Sci.*, **284**(1-2), 17-53.

Lee, D.J., Chen, Y.Y., Show, K.Y., Whiteley, C.G. and Tay, J.H. (2010), "Advances in aerobic granule formation and granule stability in the course of storage and reactor operation", *Biotechnol. Adv.*, **28**(6), 919-934.

Lee, S. and Lee, C.H. (2000), "Effect of operating conditions on CaSO4 scale formation mechanism in

nanofiltration for water softening", *Water Res.*, **34**(15), 3854-3866.
Lemaire, R., Yuan, Z., Blackall, L.L. and Crocetti, G.R. (2008), "Microbial distribution of Accumulibacter spp. and Competibacter spp. in aerobic granules from a lab-scale biological nutrient removal system", *Environ. Microbiol.*, **10**(2), 354-363.
Li, X.F., Li, Y.J., Liu, H., Hua, Z.Z., Du, G.C. and Chen, J. (2008), "Correlation between extracellular polymeric substances and aerobic biogranulation in membrane bioreactor", *Sep. Purif. Technol.*, **59**(1), 26-33.
Li, X.M., Liu, Q.Q., Yang, Q., Guo, L., Zeng, G.M., Hu, J.M. and Zheng, W. (2009), "Enhanced aerobic sludge granulation in sequencing batch reactor by Mg2+ augmentation", *Bioresour. Technol.*, **100**(1), 64-67.
Li, X., Gao, F., Hua, Z., Du, G. and Chen, J. (2005), "Treatment of synthetic wastewater by a novel MBR with granular sludge developed for controlling membrane fouling", *Sep. Purif. Technol.*, **46**(1-2): 19-25.
Li, X., Li, Y., Liu, H., Hua, Z., Du, G. and Chen, J. (2007), "Characteristics of aerobic biogranules from membrane bioreactor system", *J. Membr. Sci.*, **287**(2), 294-299.
Li, Z. and Wang, X. (2008), "Effects of salinity on the morphological characteristics of aerobic granules", *Water Sci. Technol.*, **58**(12), 2421-2426.
Lin, H., Gao, W., Meng, F., Liao, B.Q., Leung, K.T., Zhao, L., Chen, J. and Hong, H. (2012), "Membrane bioreactors for industrial wastewater treatment: A critical review", *Crit. Rev. Environ. Sci. Technol.*, **42**(7), 677-740.
Lin, H., Zhang, M., Wang, F., Meng, F., Liao, B.Q., Hong, H., Chen, J. and Gao, W. (2014), "A critical review of EPSs in MBRs: Characteristics, roles in membrane fouling & control strategies", *J. Membr. Sci.*, **460**, 110-125.
Lin, H.J., Xie, K., Mahendran, B., Bagley, D.M., Leung, K.T., Liss, S.N. and Liao, B.Q. (2009), "Sludge properties and their effects on membrane fouling in submerged anaerobic membrane bioreactors (SAnMBRs) ", *Water Res.*, **43**(15), 3827-3837.
Lin, Y.M., Liu, Y. and Tay, J.H. (2003), "Development and characteristics of phosphorus-accumulating microbial granules in sequencing batch reactors", *Appl. Microbiol. Biotechnol.*, **62**(4), 430-435.
Liu, Q.S., Tay, J.H. and Liu, Y. (2003), "Substrate concentration-independent aerobic granulation in sequential aerobic sludge blanket reactor", *Environ. Technol.*, **24**(10), 1235-1242.
Liu, X.M., Sheng, G.P., Luo, H.W., Zhang, F., Yuan, S.J., Xu, J., Zeng, R.J., Wu, J.G. and Yu, H.Q. (2010), "Contribution of Extracellular Polymeric Substances (EPS) to the sludge aggregation", *Environ. Sci. Technol.*, **44**(11), 4355-4360.
Liu, Y.Q., Liu, Y. and Tay, J.H. (2004), "The effects of extracellular polymeric substances on the formation and stability of biogranules", *Appl. Microbiol. Biotechnol.*, **65**(2), 143-148.
Liu, Y.Q., Moy, B., Kong, Y.H. and Tay, J.H. (2010), "Formation, physical characteristics and microbial community structure of aerobic granules in a pilot-scale sequencing batch reactor for real wastewater treatment", *Enzyme Microb. Technol.*, **46**(6), 520-525.
Liu, Y. and Fang, H.H.P. (2003), "Influences of Extracellular Polymeric Substances (EPS) on flocculation, settling, and dewatering of activated sludge", *Crit. Rev. Environ. Sci. Technol.*, **33**(3), 237-273.
Liu, Y. and Liu, Q.S. (2006), "Causes and control of filamentous growth in aerobic granular sludge sequencing batch reactors", *Biotechnol. Adv.*, **24**(1), 115-127.
Liu, Y. and Tay, J.H. (2002), "The essential role of hydrodynamic shear force in the formation of biofilm and granular sludge", *Water Res.*, **36**(7), 1653-1665.
Liu, Y. and Tay, J.H. (2004), "State of the art of biogranulation technology for wastewater treatment", *Biotechnol. Adv.*, **22**(7), 533-563.
Liu, Y., Xu, H., Yang, S.F. and Tay, J.H. (2003), "A general model for biosorption of Cd2+, Cu2+ and Zn2+ by aerobic granules", *J. Biotechnol.*, **102**(3), 233-239.
Liu, Y., Yang, S.F., Tan, S.F., Lin, Y.M. and Tay, J.H. (2002), "Aerobic granules: a novel zinc biosorbent", *Lett. Appl. Microbiol.*, **35**(6), 548-551.
Liu, Y., Yang, S.F., Tay, J.H., Liu, Q.S., Qin, L. and Li, Y. (2004), "Cell hydrophobicity is a triggering force of biogranulation", *Enzyme Microb. Technol.*, **34**(5), 371-379.

McSwain, B., Irvine, R., Hausner, M. and Wilderer, P. (2005), "Composition and distribution of extracellular polymeric substances in aerobic flocs and granular sludge", *Appl. Environ. Microbiol*., **71**(2), 1051-1057.

Meng, F., Chae, S.R., Drews, A., Kraume, M., Shin, H.S. and Yang, F. (2009), "Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material", *Water Res*., **43**(6), 1489-1512.

Metcalf & Eddy Inc., Tchobanoglous, G., Stensel, H.D., Tsuchihashi, R., Burton, F.L., Abu-Orf, M., Bowden, G. and Pfrang, W. (2014), *Wastewater Engineering: Treatment & Resource Recovery*, 5th Edition, New York, McGraw Hill.

Meyer, R.L., Saunders, A.M., Zeng, R.J., Keller, J. and Blackall, L.L. (2003), "Microscale structure and function of anaerobic-aerobic granules containing glycogen accumulating organisms", *FEMS Microbiol. Ecol*., **45**(3), 253-261.

Morgenroth, E., Sherden, T., Van Loosdrecht, M.C.M., Heijnen, J.J. and Wilderer, P.A. (1997), "Aerobic granular sludge in a sequencing batch reactor", *Water Res.*, **31**(12), 3191-3194.

Moy, B.Y.P., Tay, J.H., Toh, S.K., Liu, Y. and Tay, S.T.L. (2002), "High organic loading influences the physical characteristics of aerobic sludge granules", *Lett. Appl. Microbiol.*, **34**(6), 407-412.

Mutamim, N.S.A., Noor, Z.Z., Hassan, M.A.A. and Olsson, G. (2012), "Application of MBR technology in treating high strength industrial wastewater: A performance review", *Desalination*, **305**, 1-11.

Mutamim, N.S.A., Noor, Z.Z., Hassan, M.A.A., Yuniarto, A. and Olsson, G. (2013), "Membrane bioreactor: Applications and limitations in treating high strength industrial wastewater", *Chem. Eng. J.*, **225**, 109-119.

Nancharaiah, Y.V., Schwarzenbeck, N., Mohan, T.V.K., Narasimhan, S.V., Wilderer, P.A. and Venugopalan, V.P. (2006), "Biodegradation of nitrilotriacetic acid (NTA) and ferric-NTA complex by aerobic microbial granules", *Water Res.*, **40**(8), 1539-1546.

Ng, K.K., Lin, C.F., Lateef, S.K., Panchangam, S.C., Hong, P.K.A. and Yang, P.Y. (2010), "The effect of soluble microbial products on membrane fouling in a fixed carrier biological system", *Sep. Purif. Technol.*, **72**(1), 98-104.

Oleszkiewicz, J.A. and Barnard, J.L. (2006), "Nutrient removal technology in north america and the european union: A review", *Water Qual. Res. J. Canada*, **41**(4), 449-462.

Pan, J.R., Su, Y. and Huang, C. (2010), "Characteristics of soluble microbial products in membrane bioreactor and its effect on membrane fouling", *Desalination*, **250**(2), 778-780.

Peng, D.C., Bernet, N., Delgenes, J.P. and Moletta, R. (1999), "Aerobic granular sludge-a case report", *Water Res.*, **33**(3), 890-893.

Pronk, M., de Kreuk, M.K., de Bruin, B., Kamminga, P., Kleerebezem, R. and van Loosdrecht, M.C.M. (2015), "Full scale performance of the aerobic granular sludge process for sewage treatment", *Water Res.*, **84**, 207-217.

Qin, L., Liu, Y. and Tay, J.H. (2004), "Effect of settling time on aerobic granulation in sequencing batch reactor", *Biochem. Eng. J.*, **21**(1), 47-52.

Sajjad, M., Kim, I.S. and Kim, K.S. (2016), "Development of a novel process to mitigate membrane fouling in a continuous sludge system by seeding aerobic granules at pilot plant", *J. Membr. Sci.*, **497**, 90-98.

Sheng, G.P., Yu, H.Q. and Li, X.Y. (2010), "Extracellular polymeric substances (EPS) of microbial aggregates in biological wastewater treatment systems: A review", *Biotechnol. Adv.*, **28**(6), 882-894.

Shirazi, S., Lin, C.J. and Chen, D. (2010), "Inorganic fouling of pressure-driven membrane processes-A critical review", *Desalination*, **250**(1), 236-248.

Show, K.Y., Lee, D.J. and Tay, J.H. (2012), "Aerobic granulation: advances and challenges", *Appl. Biochem. Biotechnol.*, **167**, 1622-1640.

Smith, V.H. and Schindler, D.W. (2009), "Eutrophication science: where do we go from here?", *Trends Ecol. Evol*., **24**(4), 201-207.

Smith, V.H., Tilman, G.D. and Nekola, J.C. (1999), "Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems", *Environ. Poll*., **100**(1-3), 179-196.

Spettmann, D., Eppmann, S., Flemming, H.C. and Wingender, J. (2007), "Simultaneous visualisation of biofouling, organic and inorganic particle fouling on separation membranes", *Water Sci. Technol.*, **55**(8-

9), 207-210.
Sun, F.Y., Wang, X.M. and Li, X.Y. (2011), "Change in the fouling propensity of sludge in membrane bioreactors (MBR) in relation to the accumulation of biopolymer clusters", *Bioresour. Technol.*, **102**(7), 4718-4725.
Sun, X.F., Wang, S.G., Liu, X.W., Gong, W.X., Bao, N., Gao, B.Y. and Zhang, H.Y. (2008), "Biosorption of Malachite Green from aqueous solutions onto aerobic granules: Kinetic and equilibrium studies", *Bioresour. Technol*., **99**(9), 3475-3483.
Tay, J.H., Ivanov, V., Pan, S. and Tay, S. T.L. (2002), "Specific layers in aerobically grown microbial granules", *Lett. Appl. Microbiol*., **34**(4), 254-257.
Tay, J.H., Liu, Q.S. and Liu, Y. (2001), "Microscopic observation of aerobic granulationin sequential aerobic sludge blanket reactor", *J. Appl. Microbiol.*, **91**, 168 - 175.
Tay, J.H., Liu, Q.S. and Liu, Y. (2002), "Characteristics of aerobic granules grown on glucose and acetate in sequential aerobic sludge blanket reactors", *Environ. Technol.*, **23**(8), 931-936.
Tay, J.H., Liu, Y., Tay, S.L. and Hung, Y.T. (2009), *Aerobic Granulation Technology, Advanced Biological Treatment Processes*, Eds. L.K. Wang, N.K. Shammas and Y.T. Hung, New York, Humana Press.
Tay, J.H., Pan, S., He, Y. and Tay, S.T.L. (2004), "Effect of organic loading rate on aerobic granulation. I: Reactor performance", *J. Environ. Eng*., **130**(10), 1094-1101.
Tay, J.H., Liu, Q.S. and Liu, Y. (2001), "The effects of shear force on the formation, structure and metabolism of aerobic granules", *Appl. Microbiol. Biotechnol*., **57**(1-2), 227-233.
Tay, J.H., Liu, Q.S. and Liu, Y. (2001), "The role of cellular polysaccharides in the formation and stability of aerobic granules", *Lett. Appl. Microbiol*., **33**(3), 222 - 226.
Tay, J.H., Tay, S.T.L., Ivanov, V., Pan, S., Jiang, H.L. and Liu, Q.S. (2003), "Biomass and porosity profiles in microbial granules used for aerobic wastewater treatment", *Lett. Appl. Microbiol*., **36**(5), 297-301.
Tay, J.H., Yang, P., Zhuang, W.Q., Tay, S.T.L. and Pan, Z.H. (2007), "Reactor performance and membrane filtration in aerobic granular sludge MBR", *J. Membr. Sci*., **304**(1-2), 24-32.
Tay, S.T.L., Ivanov, V., Yi, S., Zhuang, W.Q. and Tay, J.H. (2002), "Presence of anaerobic bacteroides in aerobically grown microbial granules", *Microbial Ecology*, **44**(3), 278-285.
Thanh, B.X., Visvanathan, C. and Ben Aim, R. (2013), "Fouling characterization and nitrogen removal in a batch granulation membrane bioreactor", *Int. Biodeterior. Biodegrad*., **85**, 491-498.
Thanh, B.X., Visvanathan, C., Spérandio, M. and Aim, R.B. (2008), "Fouling characterization in aerobic granulation coupled baffled membrane separation unit", *J. Membr. Sci.*, **318**(1-2), 334-339.
Toh, S., Tay, J., Moy, B., Ivanov, V. and Tay, S. (2003), "Size-effect on the physical characteristics of the aerobic granule in a SBR", *Appl. Microbiol. Biotechnol*., **60**(6), 687-695.
Tsuneda, S., Nagano, T., Hoshino, T., Ejiri, Y., Noda, N. and Hirata, A. (2003), "Characterization of nitrifying granules produced in an aerobic upflow fluidized bed reactor", *Water Res*., **37**(20), 4965-4973.
Tu, X., Zhang, S., Xu, L., Zhang, M. and Zhu, J. (2010), "Performance and fouling characteristics in a membrane sequence batch reactor (MSBR) system coupled with aerobic granular sludge", *Desalination*, **261**(1-2), 191-196.
Ueda, T. and Hata, K. (1999), "Domestic wastewater treatment by a submerged membrane bioreactor with gravitational filtration", *Water Res*., **33**(12), 2888-2892.
van Dijk, L. and Roncken, G.C.G. (1997), "Membrane bioreactors for wastewater treatment: The state of the art and new developments", *Water Sci. Technol*., **35**(10), 35-41.
Vanysacker, L., Declerck, P., Bilad, M.R. and Vankelecom, I.F.J. (2014), "Biofouling on microfiltration membranes in MBRs: Role of membrane type and microbial community", *J. Membr. Sci*., **453**, 394-401.
Vijayalayan, P., Thanh, B.X. and Visvanathan, C. (2014), "Simultaneous nitrification denitrification in a Batch Granulation Membrane Airlift Bioreactor", *Int. Biodeterior. Biodegrad.*, **95**, 139 - 143.
Wang, X.M. and Li, X.Y. (2008), "Accumulation of biopolymer clusters in a submerged membrane bioreactor and its effect on membrane fouling", *Water Res*., **42**(4-5), 855-862.
Wang, X.M., Sun, F.Y. and Li, X.Y. (2011), "Investigation of the role of biopolymer clusters in MBR membrane fouling using flash freezing and environmental scanning electron microscopy", *Chemosphere*, **85**(7), 1154-1159.

Wang, Y., Zhong, C., Huang, D., Wang, Y. and Zhu, J. (2013), "The membrane fouling characteristics of MBRs with different aerobic granular sludges at high flux", *Bioresour. Technol*., **136**, 488-495.
Wang, Z., Ma, J., Tang, C.Y., Kimura, K., Wang, Q. and Han, X. (2014), "Membrane cleaning in membrane bioreactors: A review", *J. Membr. Sci*., **468**, 276-307.
Wang, Z., Wu, Z., Yin, X. and Tian, L. (2008), "Membrane fouling in a submerged membrane bioreactor (MBR) under sub-critical flux operation: Membrane foulant and gel layer characterization", *J. Membr. Sci*., **325**(1), 238-244.
WEF (2011). *Membrane Bioreactors: Water Environment Federation (WEF) Manual of Practice No. 36*, McGraw-Hill, New York.
Yang, S.F., Liu, Q.S., Tay, J.H. and Liu, Y. (2004), "Growth kinetics of aerobic granules developed in sequencing batch reactors", *Lett. Appl. Microbiol*., **38**(2), 106-112.
Yang, S.F., Tay, J.H. and Liu, Y. (2003), "A novel granular sludge sequencing batch reactor for removal of organic and nitrogen from wastewater", *J. Biotechnol*., **106**(1), 77-86.
Yilmaz, G., Lemaire, R., Keller, J. and Yuan, Z. (2008), "Simultaneous nitrification, denitrification, and phosphorus removal from nutrient-rich industrial wastewater using granular sludge", *Biotechnol. Bioeng.*, **100**(3), 529-541.
Yu, G.H., Juang, Y.C., Lee, D.J., He, P.J. and Shao, L.M. (2009), "Filterability and extracellular polymeric substances of aerobic granules for AGMBR process", *J. Taiwan Inst. Chem. Eng*., **40**(4), 479-483.
Zheng, Y.M., Yu, H.Q., Liu, S.J. and Liu, X.Z. (2006), "Formation and instability of aerobic granules under high organic loading conditions", *Chemosphere*, **63**(10), 1791-1800.
Zhu, J. and Wilderer, P.A. (2003), "Effect of extended idle conditions on structure and activity of granular activated sludge", *Water Res*., **37**(9), 2013-2018.
Zhu, L., Lv, M.L., Dai, X., Yu, Y.W., Qi, H.Y. and Xu, X.Y. (2012), "Role and significance of extracellular polymeric substances on the property of aerobic granule", *Bioresour. Technol.*, **107**, 46-54.

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