Tutor

Dr. Joan Dosta Parras
Departament d'Enginyeria Química

Grau en Enginyeria Química

Treball Final de Grau

Study of the anaerobic membrane bioreactor (AnMBR) technology for urban wastewater treatment.

Estudi de la tecnologia de bioreactors de membrana anaeròbics (BRM-An) per al tractament d'aigües residuals urbanes.

Maria del Mar Galmés Artigues

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El éxito es fácil de obtener. Lo difícil es merecerlo.

Albert Camus (1913-1960)

AGRAÏMENTS

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CONTENTS

SUMMARY

Anaerobic membrane bioreactor (AnMBR) technology has arised as an alternative option for wastewater treatment, providing many advantages such as high organic matter removal efficiency (~98%), compact process, energy recovery (biogas) and sludge reduction. It combines the advantages of the use of membranes, already proved in aerobic membrane bioreactors, and the advantages of the anaerobic digestion, widely used since 1900s.

The bioreactors can be single or a combination of various reactors, with the membrane either external or immersed. The membrane modules can be multitube (mostly used in external membrane bioreactors), flat sheet or hollow fiber modules (both used mainly in immersed membrane bioreactors). The membrane materials can be polymeric (the mostly used), metallic or ceramic. Also, the biomass can be suspended, granular (widely used in upflow anaerobic sludge blanket reactors) or attached (the most used in anaerobic fluidized-bed reactors).

The energy balances confirm that the AnMBR process can be a self-sufficient process, even an energy-producer process, diminishing GHG emissions and reduced carbon footprint.

The main limitations of the AnMBRs for urban wastewater treatment are membrane fouling and high quantity of dissolved methane in effluent. Some authors have successfully partially controlled them, but more research is still necessary in this field.

In addition, some authors have used AnMBRs for industrial wastewater treatment, with successful results: SRTs up to 230 days with HRTs between 16 h - 5 days, and the COD removal efficiency between 94-99%. However, for urban and high-solid-content wastewaters the applicability is still doubtful: low COD removal efficiency, which does not fulfill with the legislative requirements.

The firstly AnMBR commercially used for industrial wastewater treatment in the 1980s were known as Membrane Anaerobic Reactor System (MARS) and Anaerobic Digestion Ultrafiltration (ADUF). In the last decade, Kubota Corporation developed a submerged anaerobic membrane

bioreactor process, named KSAMBR process, successfully applied in food and beverages industries, and ADI Systems Inc. developed ADI-AnMBR system, specific for food wastewaters.

RESUMEN

La tecnología de biorreactores de membrana anaeróbicos (BRM-An) surgió como una alternativa al tratamiento de aguas residuales, proporcionando muchas ventajas como alta eficiencia de eliminación de materia orgánica (~98%), proceso compacto, recuperación de energía (en forma de biogás) y disminución de fangos. Esta tecnología combina las ventajas del uso de membranas, ya probada en biorreactores de membrana aeróbicos, y las ventajas de la digestión anaeróbica, ampliamente usada desde 1900.

La configuración de reactores puede constar de un único reactor o de varios, con la membrana externa o sumergida. Los módulos de membrana pueden ser de multitubo (mayormente usados para biorreactores de membrana externa), de láminas o de fibras huecas (los dos muy usados en biorreactores de membrana sumergida). Los materiales de la membrana pueden ser poliméricos (los más utilizados), metálicas o cerámicas. Además, la biomasa puede estar suspendida, granulada (las más utilizadas en los reactores UASB) o fijada a un soporte (muy utilizada en reactores anaeróbicos de lecho fluidizado).

Los balances de energía corroboran que el proceso de BRM-An puede ser autosuficiente, incluso un generador de energía, disminuyendo así las emisiones de gases de efecto invernadero y la huella de carbono.

Las mayores limitaciones de los BRM-An para el tratamiento de aguas residuales urbanas son el ensuciamiento de la membrana y la gran cantidad de metano disuelto en el efluente. Algunos autores han aconseguido controlarlas parcialmente, pero se necesita más investigación en este campo.

Además, algunos autores han usado los BRM-An para tratar aguas residuales industriales obteniendo exitosos resultados: tiempos de retención de sólidos de hasta 230 días con tiempos de retención hidráulicos de sólo 16 h – 5 días, y la eficiencia de eliminación de materia orgánica entre 94-99%. No obstante, para el tratamiento de aguas residuales urbanas y con alto

contenido en sólidos su aplicabilidad aún es dudosa: la eficiencia de eliminación de materia orgánica es demasiado baja, y no cumple con los requisitos establecidos por la ley.

El primer BRM-An usado comercialmente para tratar aguas residuales industriales en 1980 se conoce como Membrane Anaerobic Reactor System (MARS) y Anaerobic Digestion Ultrafiltration (ADUF). En la última década, Kubota Corporation desarrolló un biorreactor de membrana sumergida, el KSAMBR, aplicado exitosamente en industrias alimentarias y de bebidas, y ADI Systems Inc. desarrolló el sistema ADI-AnMBR, específico para aguas residuales de industrias alimentarias.

1. INTRODUCTION

The tight environmental regulations and standards on wastewater reuse involve the apparition of alternative processes to cope with the new stringencies. However, their technical and economic feasibilities may be taken into consideration.

Membrane bioreactor (MBR) has become a popular biological wastewater treatment technology because of the high-quality effluent, small footprint, compact facilities and reduced sludge yield. Nevertheless, the membrane fouling is a major obstacle to the widespread application (Zarragoitia-González, et al. 2008). Fouling is affected by numerous parameters such as biomass properties and process parameters that might be optimized.

The membrane bioreactor (MBR) process couples membrane technology with biological treatment. Membrane technology has become an extended separation process due to its relatively low energy requirement with no additional chemical added (Singhania, et al. 2012). The number of MBR installed worldwide has increased over the last years: in Europe and North America is preferred as wastewater treatment particularly in regions with high water scarcity (Singhania, et al. 2012).

Moreover, the anaerobic membrane bioreactor (AnMBR) technology provides the advantages of anaerobic digestion such as pollution reduction and energy production, with the advantages of membrane technology (Lin, et al. 2013). The energy production may lead to a self-sufficient process even to an energy generating process. This technology is considered as an alternative option for wastewater treatment over conventional anaerobic treatment and aerobic membrane bioreactor (MBR) technology, especially at extreme conditions such as high salinity, high temperature, high suspended solids concentrations and toxicity, which diminish or inhibit biological activity (Dereli, et al. 2012).

1.1. BIOLOGICAL PROCESS FOR WASTEWATER TREATMENT

1.1.1. DEFINITION, CHARACTERISTICS AND TYPES

The main objective of biological treatment is to eliminate organic matter from the wastewater using bacteria: they grow up transforming the pollutants into carbon source and/or energy, generating new microorganisms (biomass), CO_2, and other compounds. Additionally, biological treatments can be used for nutrient elimination process, such as nitrogen and phosphorus.

Considering the media where microorganisms grow up, the biological treatments can be splitted into two groups:

- **Suspension growth process**: microorganisms grow up as a suspension into the reactor.
- **Fixed culture or solid support process**: microorganisms are fixed onto an inert support where they grow up.

1.1.2. MICROORGANISM CLASSIFICATION

The microorganisms responsible for the biological wastewater depuration can be classified with several criteria, as shown in the following table:

Table 1. Main bacteria classification according to its metabolism.

Conditions	Bacteria	Carbon source	Electron donor	Electron acceptor	Reaction	Products
Aerobic	Heterotrophic	Organic matter	Organic matter	O_2	Aerobic oxidation	CO_2 + H_2O
Aerobic	Autotrophic	CO_2	NH_4^+, NO^{2-}	O_2	Nitrification	NO_2^-, NO_3^-
Anoxic	Heterotrophic	Organic matter	Organic matter	NO_2^-, NO_3^-	Denitrification	N_2 + CO_2 + H_2O
Anaerobic	Heterotrophic	Organic matter	Volatile fatty acids	Organic matter, H^+	Methanogenesis	CH_4 + CO_2

1.2. ANAEROBIC DIGESTION

Excess sludge from wastewater treatment (WWT) plant is usually treated in anaerobic mesophilic digesters, where the anaerobic microbiological reduction of the organic matter produces combustible gas (biogas). This biogas contains a large percentage of methane (higher than 60%). Due to the fact that the biogas production derives from organic matter removal, this process can treat a large number of wastewaters: agriculture's and farm's wastes, organic industrial and urban, urban and industrial wastewaters and WWT plants' sludge.

The main anaerobic digestion systems are:

- **Suspended**: such as continuous stirring tank reactors (CSTR), upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB).
- **Attached**: The reactor systems are anaerobic filters (AF) and anaerobic fluidized-bed reactors (AFBR), both widely used for biofilm processes.

Anaerobic digestion consists of three successive phases:

- **Hydrolysis**: hydrolytic microorganisms crack organic polymers (such as carbohydrates, lipids and proteins) into soluble shorter compounds.
- **Acidogenesis**: formed by two consecutive phases:
  - **Acidogenic phase**: soluble monomers from hydrolytic phase are fermented and converted to acid and alcoholic short chain compounds.
  - **Acetogenic phase**: acetogenic bacteria generate acetic acid and hydrogen from the previous phase products.
- **Methanogenesis**: methanogenic bacteria convert acetic acid into methane and CO_2. It is important to highlight that methanogenic step is usually the limitant step for the biomethanization process, due to the low methanogenic growth taxes.

Due to the fact that the biogas production of the WWT plant's sludge comes from COD, the supernatant from anaerobic digesters is very rich in ammoniacal nitrogen from the nitrogen associated to COD.

1.3. IMPROVEMENT OF ANAEROBIC DIGESTION TECHNOLOGIES

Anaerobic digestion (AD) is worldwide applied to reduce operating costs of the treatment by generating energy from biogas production, amongst other benefits. However, the process has many draswbacks, such as slow and incomplete degradation rates, which has lead to the apparition of “enhanced anaerobic digestion” technologies as a pretreatment to AD.

These technologies are based on the biogas formation improvement by facilitating acces to substrate, such as: **Low-frequency ultrasound pretreatment** (ultrasound causes sludge disintegration (Appels, et al. 2008)), **water electrolysis** (applied voltage (Tartakovsky, et al. 2011) results in a continuous supply of oxygen and hydrogen. The oxygen creates micro-aerobic conditions which facilitates hydrolysis and reduces the hydrogen sulfide release and hydrogen is converted to methane by hydrogenotrophic methanogens increasing methane production and a portion is escaped to the biogas (improving its combustion properties)), **oxidative pretreatment** (sewage sludge from urban wastewater treatment plant was partially oxidized by ozone (Weemaes, et al. 2000) which enhanced the post-anaerobic sludge digestion and methane production), **mechanical methods** (which consist on grinding solid particles, releasing cell compounds and creating new surface where biodegradation takes place), **chemical methods** (destruction of organic compounds by acids or alkalis), **thermal pretreatment**, **enzymatic and microbial pretreatment**, and **stimulation of anaerobic microorganisms** are examples of pretreatment improvements (van Lier, et al. 2001).

On the other hand, some technologies appeared as “intensive anaerobic digestion”, as AD enhancement based on biofilm and granules technologies, which mainly are: **upflow anaerobic sludge blanket** (UASB) reactor evolved from anaerobic clarigester (works with flocculants and gravity effect), **expanded granular sludge bed** (EGSB) digestion (evolved from UASB with fluidized/expanded sludge) and **internal circulation** (IC) reactor. Finally, **AnMBR** process is a complete different alternative technology: it is not a pretreatment, it offers methane enhancement with no necessity of facilitating the access to substrate and usually no additives needed, mainly due to the possibility of splitting HRT from SRT.

2. OBJECTIVES AND JUSTIFICATION

Since AnMBR technology has arised as an alternative option for wastewater treatment with a whole range of advantages over conventional and currently used technologies, the aim of this study is to investigate this alternative focusing on the urban wastewater treatment. Therefore, the main objectives of this study are:

- To know the characteristics of AnMBR technology: what does the technology consists in, which are the main parameters, which configurations exist, etc.
- To assess the feasibility of using AnMBR technology for urban wastewater treatment. In order to evaluate the possible advantages of this technology, energy and mass balances will be done for three different treatments (conventional treatment with SRT=5 days, conventional treatment with SRT=1 day and AnMBR treatment) and compare the results.
- To review limitations, advantages and drawbacks of AnMBR technology over other alternatives.
- Ways to avoid or manage limitations and drawbacks of AnMBRs.
- To collect information about AnMBR performances already done in lab, pilot or full scale treating industrial and urban wastewaters to compare them.

3. LEGISLATIVE FRAMEWORK

Summary of Directive 91/271/CEE:

The Directive 91/271/CEE sets out the necessary measures for European States that guarantee an adequated treatment before urban wastewater discharge. The requirements for wastewater discharge depend on the location where it is produced, classified as: sensitive, less sensitive or normal areas.

The effluent requirements for urban wastewater discharge from urban wastewater treatment plant with secondary treatment, according to current regulations in Europe, Spain and Catalonia, must be in accordance with the Directive 91/271/CEE. These requirements are reflected in the following table:

Table 2. Effluent requirements for urban wastewater discharge with secondary treatment.

Parameter	**Concentration**	**Minimum % of reduction** **(compared to influent load)**
BOD_5 (20ºC without nitrification)	25 mg $O_2 \cdot L^{-1}$	70-90%
COD	125 mg $O_2 \cdot L^{-1}$	75%
TSS	35 mg$\cdot L^{-1}$	90%

For urban wastewater discharge in sensitive areas, besides previous requirements, it must fulfill the requirements from Table 3:

Table 3. Effluent requirements for urban wastewater discharge with more stringent treatment

Parameter	**Concentration**		**Minimum % of reduction**
	(10,000 to 100,000 p.e.)	(> 100,000 p.e.)	**(compared to influent load)**
Total P	2 mg $P \cdot L^{-1}$	1 mg $P \cdot L^{-1}$	75%
Total N	15 mg $N \cdot L^{-1}$	10 mg $N \cdot L^{-1}$	90%

AnMBR studies in literature show that it fulfills the requirements for BOD, COD and TSS, but since it does not involve nutrient removal (mainly N and P), Anammox or other post-treatment must be incorporated at wastewater treatment process. These requirements are taken into account throughout this study to demonstrate the feasibility of AnMBR as alternative treatment for urban wastewaters.

4. MASS AND ENERGY BALANCES FOR DIFFERENT URBAN WASTEWATER TREATMENT PLANTS

As mentioned before, one of the most important advantages that AnMBR offers is the possibility of being a self-sufficient process, even the possibility of generating energy.

Considering conventional urban wastewater treatment plant, Figure 1 shows the basic scheme for the process (Fdz-Polanco, et al. 2010):

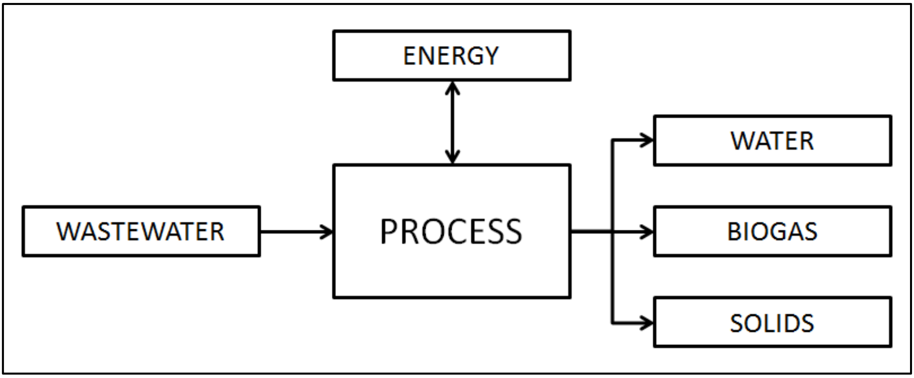


Figure 1. Simplified diagram for a wastewater treatment process (adapted from Fdz-Polanco, et al. 2010).

In this case, the wastewater contains a small amount of pollutants (<1%) that might be removed. The energy exchange is required for separation process between treated water and subproducts and waste products. Differents configurations of wastewater treatment plant have been studied in order to raise a self-sufficient process. The configurations are:

- **Conventional with SRT = 5 days**
- **Conventional with SRT = 1 day**
- **AnMBR (anaerobic membrane bioreactor replacing primary treatment)**

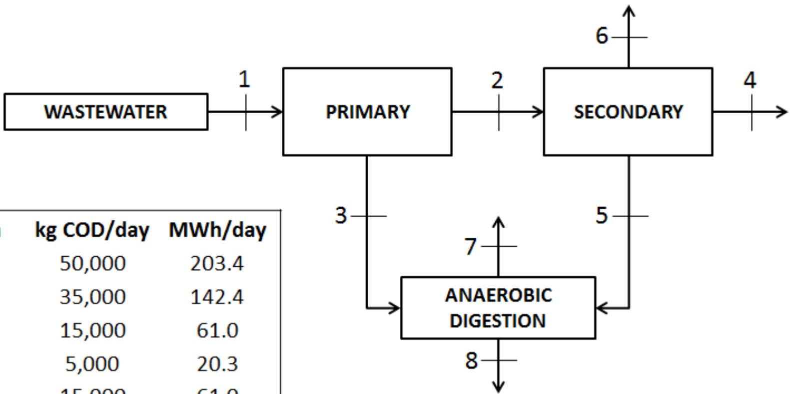
To compare the different alternatives, energy balances will be done by calculating produced and consumed energy. The produced energy corresponds to the energy content referring to kg COD eliminated (kWh/kg COD).

In order to quantify the energy content, assuming that methane combustion heat is 10,000 kcal/Nm^3:

$$\text{Energy content} = \frac{1\ \text{mol CH}_4}{2\ \text{mols O}_2} \cdot \frac{1\ \text{mol O}_2}{64\ \text{g O}_2} \cdot \frac{22.4\ \text{L CH}_4}{1\ \text{mol CH}_4} \cdot \frac{1\ \text{Nm}^3\text{CH}_4}{1000\ \text{L CH}_4} \cdot \frac{10{,}000\ \text{kcal}}{\text{Nm}^3\text{CH}_4} \cdot \frac{4.180\ \text{kJ}}{1\ \text{kcal}} \cdot \frac{1\ \text{h}}{3600\ \text{s}} = 4.068\ \text{kWh/kg COD}$$

4.1. CONVENTIONAL TREATMENT (SRT=5 DAYS)

For the conventional treatment with 5 days of SRT and 50,000 kg COD/day (Figure 2), assuming the COD elimination yield at primary decanter to be 30% and the yield of anaerobic digestion to be 45%, the energy and mass balances are:



Stream	kg COD/day	MWh/day
1	50,000	203.4
2	35,000	142.4
3	15,000	61.0
4	5,000	20.3
5	15,000	61.0
6	15,000	61.0
7	13,500	54.9
8	16,500	67.1

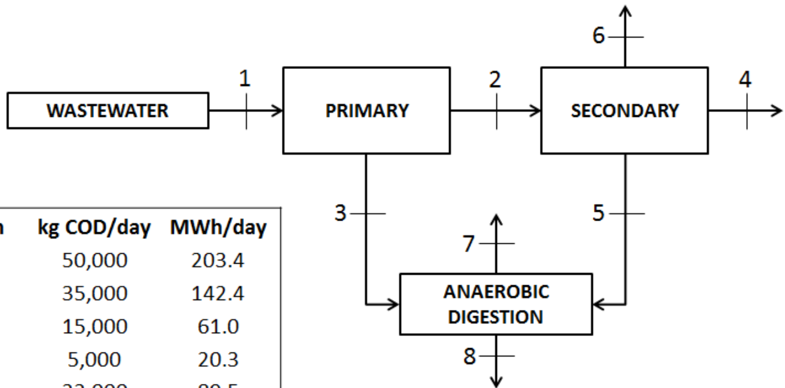
Figure 2. Energy and mass balances for a conventional wastewater treatment with SRT 5 days and 50,000 kg COD/day urban wastewater.

The energy content of each stream is calculated multiplying the COD content (kgCOD/day) and the energy calculated before (kWh/kg COD) expressed in MWh/day.

The treatment energy consumption is 25.2 MWh/day, which includes the consumption of activated sludge reactor (60%) and the rest of the plant consumption (40%). On the other hand, the methane from anaerobic digestion (stream 7) can provide (assuming that the yield to transform calorific energy to electric energy is 35%) about 19.2 MWh/day of electricity. It results on negative energy balance: this first process can not be a self-sufficient process. To improve the balance, the SRT is reduced to 1 day: the second process.

4.2. Conventional treatment (SRT=1 day)

For the conventional treatment with SRT = 1 day (Figure 3) and treating the same urban water, the energy and mass balances are:



Stream	kg COD/day	MWh/day
1	50,000	203.4
2	35,000	142.4
3	15,000	61.0
4	5,000	20.3
5	22,000	89.5
6	8,000	32.5
7	16,500	67.1
8	20,500	83.4

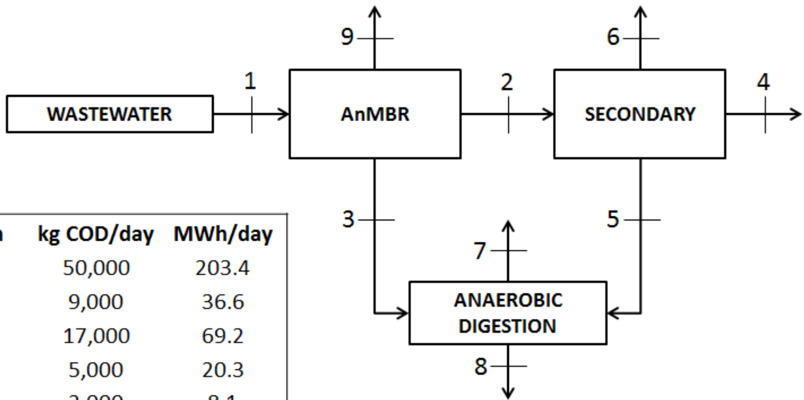
Figure 3. Energy and mass balances for a conventional wastewater treatment with SRT 1 days and 50,000 kg COD/day urban wastewater.

In this case, the secondary sludge has been increased, so the biogas production also has. The electric energy provided is about 23.6 MWh/day (also assuming the 35% yield). Furthermore, the energy required for the treatment has been decreased too due to the reduction in O_2 consumption, so it is about 18.3 MWh/day. This means that the energy balance for this second process is positive: it can be a self-sufficient process, even an energy producer process.

Due to the fact that a positive energy balance is possible and the reduction of SRT is not factible nowadays because of the way the plants operates, the AnMBR process has arised as an alternative factible option. The anaerobic membrane bioreactor placed as primary treatment is a non-energy consumer and an energy producer, so the aerobic secondary treatment acts like "finishing" step since it receives low organic load.

4.3. AnMBR

This way, the AnMBR configuration treating the same urban water (Figure 4) presents the following energy and mass balances:



Stream	kg COD/day	MWh/day
1	50,000	203.4
2	9,000	36.6
3	17,000	69.2
4	5,000	20.3
5	2,000	8.1
6	2,000	8.1
7	1,000	4.1
8	18,000	73.2
9	24,000	97.6

Figure 4. Energy and mass balances for AnMBR wastewater treatment with 50,000 kg COD/day urban wastewater.

For this configuration, the energy becoming from biogas production is the contribution of generation at both AnMBR (stream 9) and anaerobic digestion (stream 7), resulting on:

$$\text{Electricity produced} = (97.6 + 4.1) \cdot 0.35 = 35.6 \text{ MWh/day}$$

On the other hand, the energy consumption is 12.2 MWh/day which includes gas bubbling, secondary treatment requirements, and other consumptions. This way, it may be assumed that the AnMBR not only is a self-sufficient process, but also an energy-producer process.

5. STATE-OF-THE-ART OF ANAEROBIC MEMBRANE BIOREACTOR (AnMBR) TECHNOLOGY FOR WASTEWATER TREATMENT

Conventional anaerobic digestion is one of the most important processes used in industrial wastewater treatment because it combines pollution reduction with energy production (Lin, et al. 2013). This technology arised because, compared with aerobic treatment, the anaerobic digestion has lower costs of aeration and of sludge handling as no oxygen is needed and sludge yield is lower. However, the poor settling properties of the biomass in conventional anaerobic treatment result in the biomass washout, and since biomass production is lower, up to ten times less than aerobic treatment, the factibility of anaerobic treatment is doubtful.

Therefore, the widespread application is limited to the biomass retention dilemma (Lin, et al. 201): provide the enough solid retention time (SRT) for methanogens avoiding the biomass washout. The mechanisms adopted are biofilm and granule formation. This mechanisms offer biomass retention in modern high-rate anaerobic reactors (HRARs). However, they usually require a long start-up period, they are complex processes with physico-chemical and biological interactions, and are problematic under conditions of high or low temperature, low strength wastewater, high salinity, etc. (Lin, et al. 2013).

As a consequence, the use of membranes in aerobic biological waste treatment processes was getting higher interest because it offers a complete retention of all microorganisms in the bioreactor, avoiding washout problem, by using microfiltration (MF) or ultrafiltration (UF) modules (Lin, et al. 2013). Furthermore, some advantages of membrane bioreactor (MBR) were highlighted, such as reduced footprint, capacity of handling wide fluctuations in influent quality and improved effluent quality. These were the reasons for applicating membrane technology to anaerobic processes, which are attractive to research community and industrial sectors due to its advantages.

As a result, the AnMBR technology has arised as an alternative option for industrial wastewater treatments at extreme conditions that difficult granulation and biomass retention or that diminish biological activity, providing many advantages such as high organic matter removal efficiency, compact process, allows to split HRTs from SRTs, recovery of energy and sludge reduction (Dereli, et al. 2012).

5.1. COMMERCIAL DEVELOPMENT OF AnMBR

The first commercially available AnMBR systems in the 1980s applied at pilot and full scale were known as Membrane Anaerobic Reactor System (MARS) (Li, Kothari and Corrado 1985) and Anaerobic Digestion Ultrafiltration (ADUF) (Ross, et al. 1990), which were mostly used for industrial wastewater treatment. In Japan, government carried out a national project known as Aqua-Renaissance '90 which developed a wide variety of AnMBR systems mostly based on external configuration (Kimura 1991, Okamura, et al. 1991, Minami 1994).

By the 2000s, system performance, filtration characteristics, characterization of membrane foulants and membrane fouling control were the focus of many AnMBR studies. Furthermore, the success of submerged aerobic MBRs encouraged the investigation on submerged anaerobic MBRs for wastewater treatment.

In the last decade, Kubota Corporation developed KSAMBR process, which is a submerged anaerobic membrane bioreactor process successfully applied in full scale food and beverage industries (Kanai, et al. 2010). In 1997 AnMBR thermophilic solid waste treatment was patented in Japan. At 2000, 2004 and 2006 thermophilic AnMBR for solid waste, food waste and stillage treatment were implemented in Japan, respectively. Since then, Kubota developed its markets to North America and Malasia (Rizkallal Monzón 2013).

Simultaneously, with similar technology, ADI Systems Inc. developed ADI-AnMBR system specific for food wastewater treatment (Lin, et al. 2013). Nowadays, they also offer ADI-BVF (low-rate process, combining UASB with anaerobic contact systems), ADI-CGR (low-rate system), ADI-ECSB (ultrahigh-rate anaerobic process), ADI-CSTR and ADI-Hybrid systems.

5.2. AnMBR CHARACTERISTICS

Anaerobic membrane bioreactors (AnMBR) have evolved from aerobic membrane bioreactors (AMBR), with the membrane either external or immersed into the reactor. Since membranes prevent biomass washout, they enhance performance with inhibitory substances at psychrophilic/thermophilic temperatures and AnMBR can achieve high COD removals (~98%) at low hydraulic retention times (HRT) such as 3 h (Stuckey 2012).

This anaerobic biological process entails different types of microorganisms for different biological reaction, which makes its application relatively more complicated than aerobic MBR, due to its complexity of requirements (Visvanathan and Abeynayaka 2012). However, due to the necessity of reduction greenhouse gases (GHG) emissions, energy recovery and water reuse in places with water scarcity, the interest in this technology grows.

Furthermore, the interest in AnMBR technology has also arised because it is an alternative method for some cases where the application of conventional anaerobic process is incapable. For example, if wastewater contain particulates or high temperature, the granule formation and biofilm processes such as conventional upflow anaerobic sludge blanket (UASB) become ineffective. Membrane technology provides both separation of pathogens from effluent and complete retention of biomass, allowing bacteria to degrade certain types of constituents (Visvanathan and Abeynayaka 2012).

The biomass retention that the membrane technology provides is also important in AnMBR due to the fact that a reduced sludge production corresponds to less biomass production. Anaerobic microorganisms use methane as electron acceptor instead of using it to grow more microorganisms (Visvanathan and Abeynayaka 2012), and also anaerobic bacteria grow very slowly due to their low energy yields per gram of substrate (Stuckey 2012), so biomass retention becomes critical to ensure enough biomass in the reactor.

Additionally, the AnMBRs enable the nitrogen removal using Anammox (anaerobic ammonia oxidation) process (Stuckey 2012), which takes nitrite and ammonia present in wastewater to nitrogen gas (Jetten, et al. 2009). This aspect is still under study for a future application.

5.2.1. REACTOR CONFIGURATION

Mainly two configurations of single MBR exist depending on the membrane location (Singhania, et al. 2012):

- Immersed membrane bioreactor (IMBR): the membrane is submerged in the biological reactor (Figure 5) or in separate reactor (Figure 6). The way of operating is to use a vacuum or even hydrostatic head to lead the effluent through the membrane (Stuckey 2012). The advantages of having the membrane submerged is that the energy required for pumping is eliminated, although biogas needs to be recycled to provide gas bubbling to keep the membranes relatively clear from fouling (Vyrides and Stuckey 2009). In this type of configuration, the biomass is less stressed, but there are also lower fluxes which mean greater required membrane areas and lower operation costs.

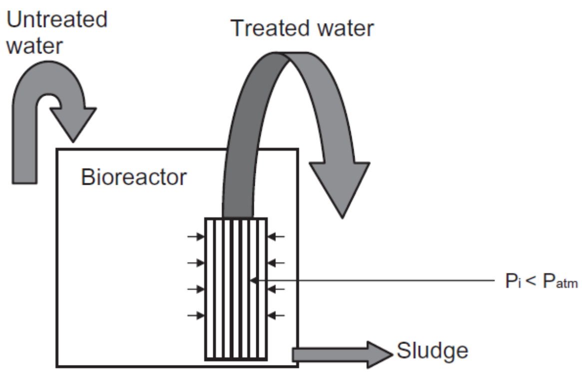


Figure 5. Internal immersed membrane bioreactor (Singhania, et al. 2012).

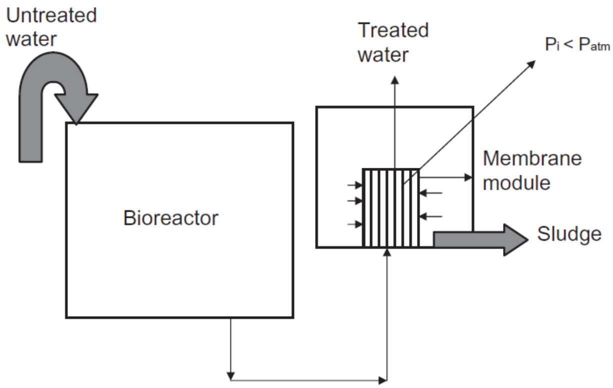


Figure 6. External immersed membrane bioreactor (Singhania, et al. 2012).

- <u>External/side stream membrane bioreactor (EMBR)</u>: the membrane is located outside the reactor as a separate unit and requires an intermediate pump. This pump can push the liquid across the membrane (Figure 7) or return the retentate to the bioreactor (Figure 8). In the first configuration the trans-membrane pressure can be higher than in IMBR due to the fact that the pump pushes the liquid to be filtered. Due to the higher trans-membrane pressure the required area for external membranes is less than for the immersed, but the energy costs are higher. Also, the membrane cleaning and replacement is easier than IMBR.

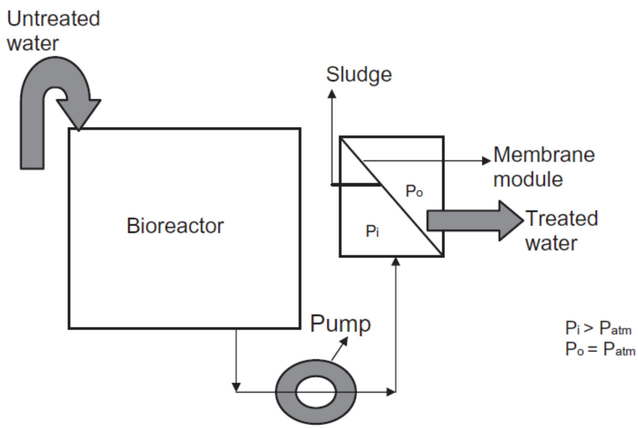


Figure 7. External non-immersed membrane bioreactor working under pressure (Singhania, et al. 2012).

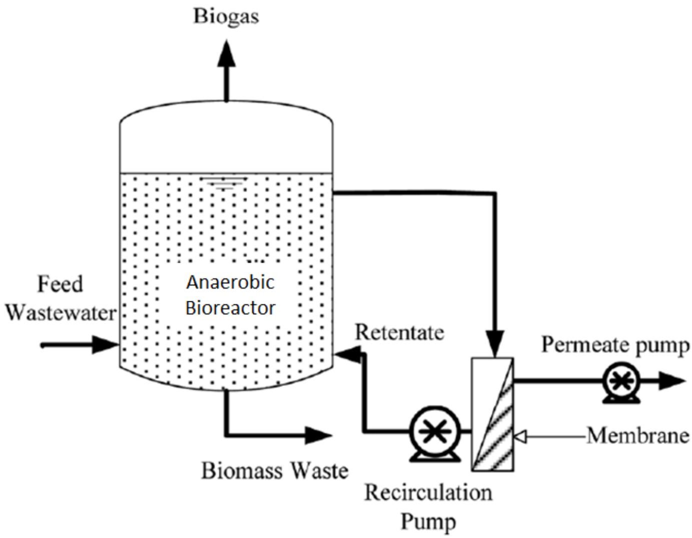


Figure 8. External non-immersed membrane bioreactor working under a vacuum (Visvanathan and Abeynayaka 2012).

Comparing the two operating modes (external and submerged), submerged membrane systems are prevailing due to both lower capital and operating costs, but these systems foul more easily so the fluxes are lower than external modules (Stuckey 2012).

Also, IMBR technology offers other advantages for wastewater treatment such as small footprint (compact process), high grade effluent and environmental sustainability (Singhania, et al. 2012).

On the other hand, MBR can be a combination of various reactors:

- Sequential membrane reactors: recently, this configuration has been developed, which consists of sequential membrane reactors where effluents from one reactor is treated by another membrane reactor with smaller pore size (Stuckey 2012).
- Two-stage configuration: in this configuration (Visvanathan and Abeynayaka 2012), the reactions of hydrolysis, acetogenesis and acidogenesis occur within the first reactor, the Hydrolytic or Acidogenic Reactor. This is followed by the second reactor, Methanogenic Reactor, where the methanogenic process takes place in (Figure 9).

The Methanogenic Reactor operates in a strictly defined optmimum pH range to avoid microorganisms' growth inhibition. In this two-stage configuration, the two reactors are operating with the optimized conditions of the respective bacteria, which is impossible for a single-stage reactor because the different species can be in direct competition with each other (Visvanathan and Abeynayaka 2012). Also, Yeoh (1997) concluded that comparing two-stage anaerobic system with single stage system, the first one can tolerate higher loading rates without affecting the removal efficiency.

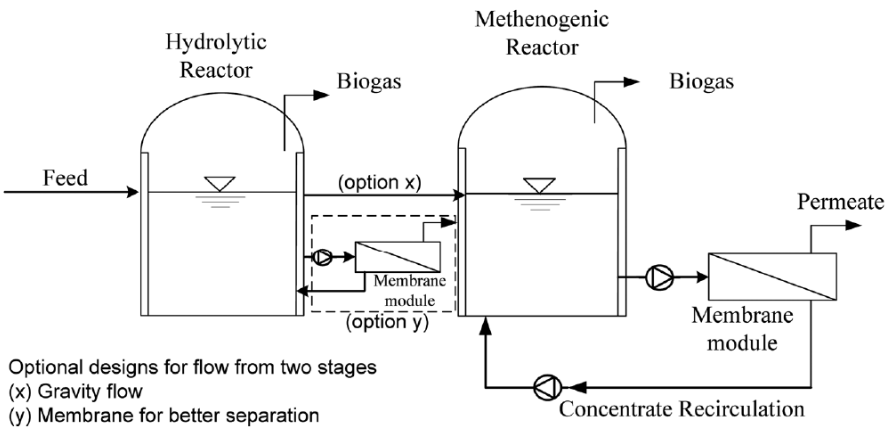


Figure 9. Two-stage AnMBR configuration (Visvanathan and Abeynayaka 2012).

5.2.2. MEMBRANE MODULES AND MATERIALS

Membrane design has evolved and refined throughout its existence. Nowadays, there are mainly three types of MF and UF membrane configurations:

- Multitube module: used mainly in EMBR process, consists on several tubular membranes arranged as tubes (Lin, et al. 2013). The main advantages are low fouling, relatively easy cleaning, easy handling of suspended solids and viscous liquids and the ability to replace or plug a damaged membrane. The disadvantages include high capital cost, low packing density, high pumping costs and high dead volume. The first MBR generation operated with tubular membranes placed in external recirculation loops, which increase energy costs of water produced (depending on the internal diameter of the tube). In addition, the higher shear stresses in the tubes and recirculation pumps can destroy the bioflocs and decrease the biological activity (Brockmann and Seyfried 1997).

- Hollow fiber module: usually used for IMBR technology due to its high packing density and cost efficiency properties (Lin, et al. 2013). This module offers more filtration surface area per unit volume (which is a real advantage over flat sheet systems), but permeability and fouling depends on the hydrodynamics conditions and performance (Lebegue, Heran and Grasmick 2008). This configuration also allows an easier cleaning of the system by a back-flush operation due to the external location of the particles.
- Flat sheet module: also usually used for IMBR process. It operates at higher specific aeration demand and achieves higher sustainable permeabilities and less cleaning (Singhania, et al. 2012). Also, its interest has grown, especially from research community (Lin, et al. 2013) due to the good stability and the ease of cleaning and replacement of defective membranes.

Lin et al. (2013) reported that membrane costs are between 46.4-72.3% of total capital costs of a full scale AnMBR. However, membrane module costs have decreased over the last years but the membrane fouling that leads to elevated energy demands has become the main contribution to overall MBR operating costs (Drews 2010). Taking membrane replacement into account, flat sheet membranes seem to be the most established technology in IMBR processes, as evidenced globally (Singhania, et al. 2012).

Also, it is important to mention the surface modification of membranes (Stuckey 2012), which can change membrane properties without altering their macroporous structure. It can be made by two main methods: coating and grafting. Coating is done dipping the membrane into a solution containing the polymer(s) with the antifouling property (coating its surface); on the other hand, grafting immobilizes hydrophilic species with covalent links onto the membranes (Hilal, et al. 2005).

On the other hand, membranes can be made mainly by three differents materials (Lin, et al. 2013):

- Inorganic (ceramic): provides high resistance to corrosion, abrasion and fouling (Ersu and Ong 2008, Baker 2000) due to its effectively backwashing. This kind of membranes seemed to be the most widely used in AnMBR technology (Ghyoot and Verstraete 1997, Imasaka, et al. 1989, Chang, et al. 1994, Beaubien, et al. 1996), since Ghyoot and Verstraete (1997) found that comparing polymer UF and ceramic MF membranes producing permeate of similar quality, ceramic membrane flux was about 200-250 $L \cdot m^{-2} \cdot h^{-1}$ which was 10 times higher than the flux achieved with polymeric membrane.
- Metallic: provides better hydraulic performance, better fouling recovery, higher strength endurable impact force and higher tolerance to oxidation and high temperature than polymeric membranes.
- Polymeric: compared to polymeric membranes, ceramic and metallic membranes are much more expensive than polymeric. This fact has resulted in a growing interest in its application. For now, the preferred materials are polyvinylidene difluoride (PVDF) and polyethersulfone (PES), almost 75% of total materials (Santos and Judd 2010), and the other materials also used for AnMBR are polyethylene (PE) (Vyrides and Stuckey 2009), polypropylene (PP) (Sainbayar, et al. 2001, Jeong, et al. 2010) and polysulfone (PS) (Jeison et al. 2005).

The Table 4 summarizes the membrane modules and materials mostly used in AnMBR and its manufacturer (Lin, et al. 2013):

Table 4. Main membrane modules and materials used in AnMBR, adapted from Lin, et al. (2013).

Material	**Module**	**Nominal pore size** (μm)	**Manufacturer**
PVDF	Hollow fiber	0.04	GE, USA
PVDF	Hollow fiber	100 kDa	Koch, USA
PVDF	Flat sheet	70 and 140 kDa	SINAP, China
PVDF	Tubular	0.03	Norit X-Flow, Inc. Netherlands
PVDF	Tubular	0.1	PCI Membrane Systems, Inc. USA
PES	Flat sheet	20-70 kDa	SINAP, China
PES	Tubular	20 kDa	Weir Envig, Paarl, South Africa
PE	Flat sheet	0.4	Kubota Corporation, Japan
PE	Hollow fiber	0.4	Mitsubishi Rayon, Japan
PP	Hollow fiber	0.45	Sumitomo Electric Fine Polymer Inc., Japan
PSF	Tubular	0.2	Triqua, Netherlands
Ceramic	Tubular	40 kDa	Aquatech Memtuf, Korea
Ceramic	Tubular	0.2	Atech Innovations, Germany
Metallic	Tubular	1.0	Fibertech Co., Ltd, Korea

5.2.3. BIOMASS

Biomass production is an important issue in wastewater treatment and its purificacion from the effluent is critical for its implementation. Taking the separation into account, there are three main mechanisms for biomass retention (Dereli, et al. 2012):

- Settling: consists on bringing time to settle down the suspended biomass, by adding or not adding chemicals (usually chemicals are added).
- Attachment: the biomass is linked to “carriers” which can be static (more common) or fluidized (similar to granulation).
- Granulation: is the most commonly applied, such as in Upflow Anaerobic Sludge Bed (UASB), Expanded Granular Sludge Bed (EGSB) and Internal Circulation (IC)

reactors (van Lier, et al. 2001). This mechanism is characterized by the formation of microbial aggregates with various functionalities (Hulshoff Pol, et al. 2004) depends on differents aspects, such as hydraulic conditions, wastewater characteristics, physico-chemical parameters, etc. Successful granulation in anaerobic high rate reactors results by bacterial selection mechanisms (as a rule of thumb, at short hydraulic retention times, i.e., <2 days). Although this technology is feasible for anaerobic treatment, there are certain limitations such as high suspended solids (SS), high temperature, fat, oil and grease (FOG) content, toxicity, high salinity, drastic changes in organic loading rate (OLR) and significant HRT fluctuations.

Moreover, the anaerobic biological process consists of three main biochemical stages: hydrolysis, acid formation and methane formation, carried out by different bacteria such as Clostridium spp, Peptococcus anaerobs, Bifidobacterium spp, Desulphovibrio spp, Corynebacterium spp, Lactobacillus, Actinomyces, Staphylococcus and Escharichia coli. This way, the involved bacteria can be splitted into three types:

- Hydrolitic bacteria: the main remarkable characteristic is that this bacteria, such as acetogens, are facultative, which means that the microorganisms can operate in both situations: with oxygen presence and absence. Also, the electron acceptor can be oxygen or other inorganic compounds.
- Acetogens: the main groups are fermentative acetogens and homoacetogens, which are facultative bacteria, more tolerant to environmental changes and fast growers. Also, homoacetogens are the mos concerned today (Khanal 2008) because of their ability to produce acetate. Acetogens have higher growth rate in mesophilic range (Adamse 1980) even though with specific substrates the higher growth rate is optimum at thermophilic conditions (Weigel and Oka 1981).
- Methanogens: about 75% of methane production is from decarboxylation of acetate and the rest is from CO_2 and H_2 (McCarty and Smith 1986). The main groups of bacteria are hydrogenetrophic methanogens and aceticlastic methanogens. Methanogens are archaea, which includes the rods (Methanobacterium,

Methanobasillus) and spheres (Methanococcus, Methanothrix and Methanocamia). However, Methanothrix and Methanocamia are the only organisms able to produce methane from acetate.

5.3. LIMITATIONS

As mentioned earlier, athough AnMBRs offer many advantages, there are several limitations: membrane fouling and dissolved methane in effluent, as most important.

5.3.1. FOULING

Basically, membrane fouling is the main bottleneck for the complete applicability of AnMBRs. The fouling can be classified into two categories (Visvanathan and Abeynayaka 2012):

- Reversible: this type of fouling can be removable from the membrane with appropriate physical cleaning.
- Irreversible: normally caused by strong attachment of particles, this type of fouling might be removed by chemical cleaning.

Also, the fouling can take place on the membrane surface or into the pores, either as cake layer formation by bio-cells deposition or the inorganic precipitation on membrane surface (Bailey, Hansford and Dold 1994), and which combination causes drastic drops in membrane permeability (Choo and Lee 1996).

Figure 10 shows a schematic list of parameters that affect membrane fouling:

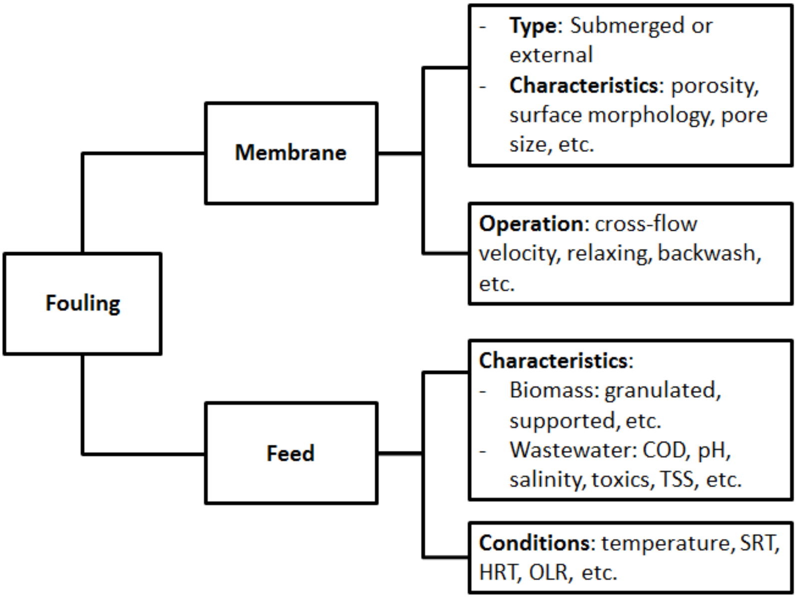


Figure 10. Parameters affecting membrane fouling for MBR (adapted from Dereli, et al. 2012 and Stuckey 2012).

The parameters that affect membrane fouling can be resumed in:

a.) Membrane

Type (configuration):

- Submerged/immersed: in this configuration biogas needs to be recycled to provide gas bubbling to keep the membranes relatively clear from fouling (Vyrides and Stuckey 2009). The fouling is higher if gas bubbling is not controlled properly.
- External/side-stream: this type of configuration requires an intermediate pump to push the liquid across the membrane, so the transmembrane pressure is higher. This fact helps to reduce fouling since cross-flow velocity keep the membranes clean. Also the membrane cleaning and replacement is easier than IMBR. However, the cross-flow velocity can not exceed 2 $m \cdot s^{-1}$ if biomass stress wants to be avoided.

Characteristics:

- Material: hydrophobic membranes foul easily in contrast to hydrophilic surfaces on which fouling is often reversible (Stuckey 2012). However, most commercial polymeric membranes are made from hydrophobic polymers such as polysulfone (PS), polyethersulfone (PES), polypropylene (PP), polyethylene (PE) and polyvinylidene difluoride (PVDF), due to their chemical, thermal and mechanical properties and resistances.

- Surface morphology: modifying membrane surface by coating and or grafting minimizes membrane biofouling due to the anti-adhesion property and anti-bacteria function (Stuckey 2012). For example, Sainbayar et al. (2001) modified a polypropylene membrane of an AnMBR with ozone and graft polymerization: the flux increased 13.5% over a virgin membrane (the increasing depends on the degree of grafting). Another example, Li et al. (2010) modified polypropylene microporous membranes of a submerged AnMBR by sequential photoinduced graft poymerisation of acrylic acid and another with acrylamide: they showed better filtration performances than unmodified membrane, and the acrylic acid grafted membrane showed better performance than the acrylamide modified membrane.
- Pore size: disminishing pore size do not always lead to lower fluxes and/or better quality effluents, due to the apparition of "gel layer", a fouling layer that acts as a secondary membrane to control both the flux and COD removal (Stuckey 2012). However, Judd (2006) states that the effect of pore size correlates with the feed characteristics and particles size distribution. Moreover, Le-Clech (2006) concluded there was no clear advantage of using tight membranes, so this fact has led to conflicting trends with no consistency between pore size and hydraulic performance (Stuckey 2012).

Operation:

- Cross-flow velocity: the cross-flow velocity applied on biomass causes bioflocs' size reduction, which leads to increase membrane fouling (Visvanathan and Abeynayaka 2012).

b.) Feed

Characteristics:

- Biomass: granulated biomass usually involves more membrane fouling than attached static biomass, due to its tendency to deposite in membrane and form a “gel layer”. This fact is typically controlled with cross-flow velocity in external membranes but is very problematic in submerged membranes. Also, the mechanical stress applied on the biomass during the pumping causes size reduction of bioflocs (Visvanathan and Abeynayaka 2012), which tends to increase fouling as shown in Lin et al. (2011) studies.
- Wastewater:
  - pH: it affects mainly on bacteria activity. The optimum pH of acetogens/acidogens is 5.5-7.8 while optimum pH of methanogens is 6.8-7.8, smaller range than acetogens. The pH drop can be caused by accumulation of acetic acid due to the slow growth rate of methanogens and high rate of acetogens. This drop can inhibit methanogenesis, and therefore, it is necessary to maintain reactor pH by methods such as separate reactor operation and alkalinity addition (Visvanathan and Abeynayaka 2012). However, de Gioannis (2008) demonstrated that AnMBRs are able to adapt the bacteria to adverse conditions if adequate time is given.
  - Chemical composition: precipitates such as struvite ($MgNH4PO4 \cdot 6H2O$) (Doyle and Parsons 2002) and other phosphate and calcium salts can foul membranes, especially inorganic membranes (Kang, Yoon and Lee 2002), since struvite can deposit together with bioflocs and make a strong barrier (Visvanathan and Abeynayaka 2012). Mainly, the inorganic ions constituting gel layer are Mg, Al, Fe, Ca and Si, as shown in Wang, et al. (2008) study using scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX). However, organic foulants interact with inorganic precipitates and enhace the formation of gel layer (Costa, de Pinho and Elimelech 2006). In anaerobic systems, the concentration of both ammonia and carbonate ions is much higher than aerobic systems due to

the higher loads and protein hydrolysis and the chemistry of carbon dioxide equilibrium, so the precipitation of these ions is preferred (Stuckey 2012).

- Salinity: high salinity stresses the microbial species, and has inhibitory/toxic effects on nonadapted biomass. These conditions have nocive effects on anaerobic processes, such as long adaptation time and negative impact on granule stability. However, AnMBRs provide better adaptation to salinity regardless of their granulation properties (Dereli, et al. 2012). This kind of stress increases the SMP production and thus increases the membrane fouling.
- Toxics/inhibitori substances: the toxic/inhibitori effects can be resumed as problems with granulation (Dereli, et al. 2012), a decrease of steady state biogas generation and accumulation of acids (Visvanathan and Abeynayaka 2012). Also, suspended cells systems are more susceptible for toxicants than biofilm or granular sludge based systems (Dereli, et al. 2012). This way, AnMBR guarantees the total retention of bacteria, enabling the better adaptation to toxic compounds. This fact reduces the bacteria stress and thus the membrane fouling. The toxic and inhibitori substances can be heavy metals, chlorinated hydrocarbons and cyanides present in wastewater, byproducts such as ammonia, sulfide and volatile datty acids, and inorganic nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}), traces of cobalt (Co) and nickel (Ni) (Visvanathan and Abeynayaka 2012).
- FOG: fat, oil and grease (FOG) have inhibitori effects on methanogenic and acetogenic bacteria (Hwu 1997) due to the adsorption of a lipid layer around biomass particles which limits the transport of substrate and nutrients (Pereira, et al. 2005). This fact results in biomass flotation (Rinzema, Alphenaar and Lettinga 1989), affecting more to the flocculent sludge than granular sludge because of its higher specific surface area (Hwu 1997), and also thi fact affects bacteria activity, which is clearly decreased due to the mass transfer limitations (Dereli, et al. 2012). As a result, the high FOG content leads to biomass flotation which can increase membrane fouling. As a consequence, a pretreatment step is required

for lipid removal if high lipid content wastewater want to be treated by anaerobic high rate reactors (Rajeshwari, et al. 2000).

- TSS: wastewaters coming from industries such as potato processing, meat processing and slaughterhouses usually have high SS concentrations which deteriorates the sludge methanogenic activity (Dereli, et al. 2012) and fouls rapidly the membrane. However, the high biomass retention in AnMBR leads to high digestion efficiency and to an effluent free of SS, with the drawback of high membrane fouling.

Conditions:

- Temperature: at high temperatures, the production of extracellular polymeric substances (EPS) decreases, which are mainly in charge of biomass aggregation, resulting in a decrease of this aggregation and a higher fouling (Dereli, et al. 2012). Also, at thermophilic conditions the biomass immobilization is more difficult than at mesophilic conditions, due to the formation of dispersed sludge with poor settling characteristics (Soto, Mendez and Lema 1992). However, at low temperatures, hydrolysis rate decreases (Veeken and Hamelers 1999) leading to lower COD removals and the half-rate constant for methanogens seems to increase (Speece 1996) which means higher effluent VFA levels, an unwanted situation.
- OLR: organic shock loads can cause deterioration of anaerobic reactor performance due to the accumulation of volatile fatty acids (VFA), the release of EPS/SMP, drop in pH and flotation of granular sludge, and all of them cause membrane fouling.

Additionally, taking into account the previous parameters and which are wanted to be avoided and which to be enhanced, there are three main categories of managing fouling in AnMBRs (Stuckey 2012):

- Operating at high fluxes for short periods of time and then relaxing/backflushing and cleaning the membranes with aggressive acids, bases and/or oxidants. This aggressive cleaning can damage the membrane and reduce its lifetime, and also it should be minimized, due to the fact that the membrane needs to be removed offline (Singhania, et al. 2012).

- Operating at below “critical flux” levels and relaxing/backflushing and cleaning occasionally when necessary. The physical cleaning (backwashing, gas bubbling, etc.) can be done more frequently than chemical cleaning as it can be done online in few minutes (Jiang, et al. 2003), whereas chemical cleaning frequency can be several days, months or even years (Murakami, et al. 2000).
- Operating in such a way to minimize SMP/colloid production, using hydrodynamics to minimize fouling layer or treating the reactor contents to remove the primary foulants.

The last way seems to be the optimal and includes strategies such as:

- Controlling the previous parameters by operating at optimal values.
- Intermittent gas sparging: Vyrides and Stuckey (2009) found that the optimal gas sparging for reducing energy consumption was 10 min on and 5 min off. This strategy leads to an increased thickness of fouling layer.
- Precipitating the key foulants: using activated carbon, cationic polymers, biopolymers, EDTA or metal salts. For example, Park et al. (1999) demonstrated that the addition of 5 $g \cdot L^{-1}$ of powdered activated carbon (PAC) into AnMBRs enhanced both flux and COD removal.
- Addition of non-degradable particles with low specific gravity that physically scour the membrane surface. For example, Akram (2007) added ion exchange resins (IX) during organic shock loads in a submerged AnMBR and it enhanced the flux across the membrane. It is necessary long acclimatization time and almost 5 $g \cdot L^{-1}$ of IX for improving stability during shock period.
- Elevation of membrane: Kim, et al. (2008) founded that a good strategy to control fouling is to vertically elevate the membrane in the reactor. This divides the reactor into two zones: upper and lower zone. In aerobic bioreactors where excess aeration is commonly the anti-fouling strategy, if the lower zone is more concentrated in suspended solids than the upper, the air bubbled is only supplied at the upper zone at

the membrane, so the air consumption is less because it has less superficial fouling to treat.

- Ultrasonic irradiation: some authors (Xu, et al. 2011, Sui, Wen and Huang 2008, Pendashteh, et al. 2011) have found that the application of ultrasonic irradiation can be effectively used to control membrane fouling.
- Dialyzer-zeolite: the use of the dialyzer-zeolite unit can be useful when membrane scaling is caused by inorganic precipitates, but it is successful only with ceramic membranes (Skouteris, et al. 2012).
- Continuous critical flux determination: Jeison and van Lier (2006) operated two submerged AnMBRs with a new operation strategy based on a continuous critical flux determination for avoiding excessive cake-layer accumulation on membrane surface. Therefore, each time a cake-layer formation was detected, a decrease in membrane flux or an increase in cross-flow velocity was immediately applied. Then, the proposal allows the MBR to operate around the critical flux all the time, minimizing the maintenance and maximizing the efficiency of the performance.

5.3.2. DISSOLVED METHANE IN EFFLUENT

On the other hand, the other important limitation for AnMBR complete applicability is the high quantity of dissolved methane in the effluent. This fact is very important at low temperatures because the gases solubility increases, e.g., the methane solubility at 15ºC is 1.5 times higher than at 35ºC, which can be a very important fraction of total methane production (Smith, et al. 2012). Furthermore, at 35ºC Kim et al. (2011) reported that 30% of the methane generated was at liquid phase and at 15ºC Smith et al. (2011) observed it was about 50%, thus underscoring the importance of methane recovery.

In addition, the presence of TMP forces the generated methane by methanogens present in the biofilm to cross the membrane and to be retained into the permeate stream, oversaturating the AnMBR permeate (Smith, et al. 2012). This way, the dissolved methane present in liquid phase from gas-liquid equilibria and dissolved methane in effluent from biological activity in the biofilm make the process to require a post-treatment step to be an energy-neutral treatment and a process free of greenhouse gas emissions.

The main ways of dissolved methane recovery are:

- Methane stripping with air (Hartley and Lant 2006, Bae, Kim and McCarty 2011): the energy demands associated is low (less than 0.05 $kWh \cdot m^{-3}$ of AnMBR permeate (Bae, Kim and McCarty 2011)); however, since methane can react with oxygen in the air, the resulting mixture from the stripping has potential explosion hazards, and also the efficiency of removing dissolved methane from AnMBR effluent with this practice is not well established yet.
- Degassing membrane (Bandara, et al. 2011): this type of membranes have the characteristic of being permeable to gases but not to liquids. Higher efficiencies at lower temperature are reached as a result of increased methane solubility at lower temperatures (Bandara, et al. 2011). However, the energy requirements for degassing are higher than the energy recovered (Bandara, et al. 2010 showed that the energy requirements were 300 times the amount of energy associated to the recovered methane).
- Down-flow Hanging Sponge (DHS) reactor (Hatamoto, et al. 2010): this reactor is characterized for the biological methane oxidation by methanotrophs, which can oxidate up to 95% of the total dissolved methane. However, energy recovering is not feasible since methane is oxidized.

5.4. ANMBR PERFORMANCES

In order to compare AnMBR performances from literature, the information has been splitted into three groups:

- **Industrial wastewaters:** AnMBR technology has been widely used in industrial wastewaters and has the major portion of experiences from the literature.
- **High suspended solid content wastewaters:** the feasibility of replacing primary and secondary treatment by AnMBR process is being studied for high suspended solid content wastewater, which has future prospects.
- **Urban wastewaters:** AnMBR process has only been applied at lab and pilot scale, and it is still under study.

5.4.1. AnMBR TREATING INDUSTRIAL WASTEWATER

Table 5. Summary of AnMBR performances for industrial wastewater treatment (adapted from Lin et al. 2013).

Influent			Treatment	Operation parameters				Effluent		References
COD ($g \cdot L^{-1}$)	TSS ($g \cdot L^{-1}$)	pH	Reactor + Membrane	Retent. time	T (ºC)	OLR ($kgCOD \cdot m^{-3} \cdot day^{-1}$)	Flux (LMH)	·COD ($mg \cdot L^{-1}$) ·COD removal(%)	·TSS ($mg \cdot L^{-1}$) ·TSS removal(%)	
Cheese whey										
68.6	1.35	6.5	CSTR 5L + MF 0.2 µm external	HRT=1 d	37	-	139.5	- 98.5	- 100	(Saddoud, Hassairi and Sayadi 2007)
68.6	1.35	6.5	CSTR 15L + MF 0.2 µm external	HRT=4 d SRT=29.7-78.6 d	37	19.78	139.5	- 98.5	- 100	(Saddoud, Hassairi and Sayadi 2007)
Olive-mill wastewater										
350-500	1-1.5	6.5-7.8	PABR 15L + UF ceramic tubular 25 kDa external	HRT= 16.7h	35	-	80-450	<30 >95	- -	(Stamatelatou, et al. 2009)
Brewery wastewater + surplus yeast										
21	12	6.9	CSTR 4.5L + ceramic tubular 0.2µ external	-	30	12	4-20	190 99	0 100	(Torres, et al. 2011)

Table 6. (Continued) Summary of AnMBR performances for industrial wastewater treatment (adapted from Lin et al. 2013).

Influent			Treatment	Operation parameters				Effluent		References
COD ($g \cdot L^{-1}$)	TSS ($g \cdot L^{-1}$)	pH	Reactor + Membrane	Retent. time	T (ºC)	OLR ($kgCOD \cdot m^{-3} \cdot day^{-1}$)	Flux (LMH)	·COD ($mg \cdot L^{-1}$) ·COD removal(%)	·TSS ($mg \cdot L^{-1}$) ·TSS removal(%)	
Kraft evaporator condensate										
10	-	-	UASB 10L + flat-sheet PVDF 140 kDa submerged	HRT=5.8 d SRT=230 d	55	3.1	2.4	- 97-99	- -	(Xie, et al. 2009)
Petrochemical wastewater										
19.1	-	7.2	CSTR 23L + Kubota flat panel 0.45µm submerged	HRT=31.5h SRT=175 d	37	14.6	8.5-16	612 98	- -	(Van Zyl, et al. 2008)
High concentration food wastewater										
2-15	0.6-1.0	7	CSTR 400L + flat-sheet PES 20-70kDa external	HRT=60 h SRT=50 d	37	<4.5	-	141-2388 81.3-94.2	- -	(He, et al. 2005)

AnMBR performance for industrial wastewater treatment is characterized for temperatures mainly higher than 35 ºC with SRTs up to 230 days, but with HRTs between 16h and few days (5-6 d). Additionally, the COD removal efficiency is higher than 94% and the TSS removal is nearly complete, so the applicability of AnMBR is proved to be enough, in most cases, to reach the requirements from legislation.

5.4.2. AnMBR TREATING HIGH-SOLID-CONTENT WASTEWATER

Table 7. Summary of AnMBR performances for high-solid-content wastewater treatment.

Slaughterhouses									
Influent			Treatment	Operation parameters				Effluent	References
COD ($g \cdot L^{-1}$)	TSS ($g \cdot L^{-1}$)	pH	Reactor + Membrane	Retent. time	T (ºC)	OLR ($kgCOD \cdot m^{-3} \cdot day^{-1}$)	Flux (LMH)	·COD ($g \cdot L^{-1}$) ·COD removal(%)	
5.2-11.7	0.57-1.69	6.8-7.8	UASB granulated	-	25-35	11	-	- 85	(Rajeshwari, et al. 2000)
5.2-11.7	0.57-1.69	6.8-7.8	UASB flocculated	-	25-35	5	-	- 80-89	(Rajeshwari, et al. 2000)
5.2-11.7	0.57-1.69	6.8-7.8	Anaerobic filter	-	25-35	2.3	-	- 85	(Rajeshwari, et al. 2000)
5.2-11.7	0.57-1.69	6.8-7.8	Anaerobic contact	-	25-35	3	-	- 92.6	(Rajeshwari, et al. 2000)
10.17	-	7.5-7.7	CSTR 50L + MF 100kDa external	HRT= 1.66d	37	8.23	<3	0.338 94	(Sayadi and Saddoud 2007)
10.58	-	7.5-7.7	FBR 25L + MF 100 kDa external	HRT= 1.25d	37	12.7	<3	0.196 98.75	(Sayadi and Saddoud 2007)

Table 8. (Continued) Summary of AnMBR performances for high-solid-content wastewater treatment.

Potato-maize wastewater								
Influent			Treatment	Operation parameters			Effluent	References
COD ($g \cdot L^{-1}$)	TSS ($g \cdot L^{-1}$)	pH	Reactor (followed by membrane filtration)	Retent. time	T (ºC)	OLR ($kgCOD \cdot m^{-3} \cdot day^{-1}$)	·COD ($g \cdot L^{-1}$) ·COD removal(%)	
9.1	2.7-7.1	6-11	UASB 1.8L	HRT=5d	35	1.83	1.71 81.3	(Kalyuzhnyi, Estrada and Rodriguez 1998)
11	-	-	Unified anaer. fermenter-filter (UAFF)	HRT=9.5d	21	1.16	- 96	(Landine, et al. 1983)
18.1	2.7-7.1	6-11	UASB 1.8L	HRT=1.3d	35	13.89	6.61 63.4	(Kalyuzhnyi, Estrada and Rodriguez 1998)
18	-	-	UASB	HRT=3.6d	20	5	- 75	(Koster and Lettinga 1985)
9	1.1-2.6	6.6-9	UASB 1.8L	HRT=1.8d	35	5.02	0.58 93.6	(Kalyuzhnyi, Estrada and Rodriguez 1998)
1.95	-	-	UASB	HRT=0.3d	31-35	7	- 83	(van Wambeke, et al. 1990)

On the other hand, for high-solid-content wastewater, it presents moderate-high OLRs and the HRTs are about only few days (less than 10 days) to prevent SS deposition as membrane fouling, but COD removal efficiency is about 80-90% in most cases with effluent COD concentration higher than 0.38 $g \cdot L^{-1}$ (higher than legislative values). This results show that the feasibility of AnMBR application for full scale is still doubtful: more research is needed in this area.

5.4.3. AnMBR TREATING URBAN WASTEWATER

Table 9. Summary of AnMBR performances for urban wastewater treatment.

Urban										
Influent			Treatment	Operation parameters				Effluent		References
COD ($mg \cdot L^{-1}$)	TSS ($g \cdot L^{-1}$)	pH	Reactor + Membrane	Retent. time	T (ºC)	OLR ($kgCOD \cdot m^{-3} \cdot day^{-1}$)	Flux (LMH)	·COD ($g \cdot L^{-1}$) ·COD removal(%)	·TSS ($g \cdot L^{-1}$) ·TSS removal(%)	
425	294	7.6	CSTR 60L + MF flat-sheet PVDF 140 kDa subm.	HRT=10 h	30	1	11	51 88	<0.8 >99.5	(Chen, et al. 2011)
302.1	120	7.3	UASB 45L + flat-sheet dynamic Subm.	HRT=8 h	10-15	0.9	65	120.8 57.7	0-15 -	(Zhang, et al. 2010)
38-131	-	6.4	CSTR 10L + PVDF 0.1µm 200 kDa external	HRT=12-48 h SRT=19-217 d	25	0.03-0.11	-	18-37 55-69	- -	(Kim, Baek and Pagilla 2010)
259.5	-	-	UASB 12.9L + non-woven fabric PET 0.64µm sub.	HRT=2.6h	15-20	2.36	5	77.5 -	- -	(An, et al. 2009)
350-500	1-1.5	6.5-7.8	CSTR 15L + Flat-sheet CA 0.2µm external	HRT= 16.67h	35	-	80-450	<30 >95	- -	(Kocadagistan and Topcub 2007)
84	120	7.5	CSTR 10L +PVDF 0.1µm 200kDa ext.	HRT=48h SRT=19d	32	0.03	-	25 58	- -	(Baek and Pagilla 2006)

Table 10. (Continued) Summary of AnMBR performances for urban wastewater treatment.

Urban										
Influent			Treatment	Operation parameters				Effluent		References
COD ($mg·L^{-1}$)	TSS ($g·L^{-1}$)	pH	Reactor + Membrane	Retent. time	T (ºC)	OLR ($kgCOD·m^{-3}·day^{-1}$)	Flux (LMH)	·COD ($g·L^{-1}$) ·COD removal(%)	·TSS ($g·L^{-1}$) ·TSS removal(%)	
540	-	-	CSTR 180L + MF hollow fiber 0.2µm external	HRT=6h	25	2.16	7.5	65 88	- -	(Lew, et al. 2009)
685	380	7.2	CSTR 50L + UF 100kDa external	HRT=15h SRT>140d	37	2	3.5-13	87.8 88	0 100	(Nagata, et al. 1989)
426.8	6	-	AnMBR 5L + plate and frame 0.45µm subm.	HRT=10h SRT=30d	25-30	0.18	-	60.8 84	- -	(Huang, Ong and Ng 2013)
426.8	9.3	-	AnMBR 5L + plate and frame 0.45µm subm.	HRT=10h SRT=60d	25-30	0.12	-	60.8 85	- -	(Huang, Ong and Ng 2013)
426.8	9.9	-	AnMBR 5L + plate and frame 0.45µm subm.	HRT=10h SRT=90d	25-30	0.13	-	61.6 86	- -	(Huang, Ong and Ng 2013)

For treating urban wastewaters, the HRTs are only about few hours in most cases (2-15 h), getting 30-90 days of SRTs. These characteristics are favourable to AnMBR applicability. However, the OLR are low (between 0.03 and 2.4 kg $COD·m^{-3}·day^{-1}$), and the COD removal efficiency is about 50-80%, with COD concentrations higher than 18 $g·L^{-1}$ at ambient temperatures (10-35 ºC), which is still the major obstacle for AnMBR application due to the requirements from legislation (COD concentration must be ≤125 mg $O_2·L^{-1}$).

5.5. ADVANTAGES AND DRAWBACKS

After all the aforesaid, AnMBR technology presents advantages and disadvantages or drawbacks that must be highlighted. These issues have been splitted into three tables: comparing AnMBR technology with aerobic MBR, anaerobic conventional treatment and aerobic conventional treatment treating the same wastewater (Table 11); comparing AnMBR performances treating industrial, high-solid-content and urban wastewaters (Table 12); and drawbacks of operating AnMBRs with different characteristics or parameters (Table 13). Then **the advantages and drawbacks of using AnMBR technology** can be summarized as:

Table 11. Advantages, disadvantages and drawbacks of using AnMBR, AeMBR, conventional anaerobic treatment or conventional aerobic treatment treating the same wastewater.

Technology	Advantages	Drawbacks/disadvantages	Remarks
AnMBR	-High COD removal efficiency leading high effluent quality with low sludge production -High OLRs and total biomass retention -Low energy requirement and bioenergy recovery with low footprint -Startup less than 2 weeks	- Moderate temperature sensitivity	Depending on the wastewater, pre- or post-treatment may be required.
AeMBR	-High COD removal efficiency with excellent effluent quality -High/moderate OLRs and total biomass retention -Startup less than 1 week	- High/moderate sludge production - High energy requirement with no possibility of bioenergy recovery	
Convent. anaerobic treatment	-High COD removal efficiency with low sludge production -High OLRs -Low energy requirement and bioenergy recovery	- Moderate/poor effluent quality - High/moderate footprint - Low biomass retention and low/moderate temperature sensitivity - The startup can be 2-4 months	Despite the drawbacks, it is widely used with measures to diminish them.
Convent. aerobic treatment	-High COD removal efficiency with high effluent quality -Low temperature sensitivity -Startup between 2-4 weeks	- Tolerates moderate OLRs - High sludge production and high footprint - Low-moderate biomass retention - High energy requirement and no possibility of bioenergy recovery	Despite the drawbacks, it is widely used with measures to diminish them.

On the other hand, **the advantages and drawbacks of using AnMBRs for different wastewaters** can be summarized as:

Table 12. Advantages, disadvantages and drawbacks of treating different wastewaters using AnMBRs.

Wastewater	Advantages	Drawbacks/disadvantages	Remarks
Industrial	- Very high SRT and low HRT - High COD and TSS removal efficiency - High OLR and fluxes are reached	- Sometimes, COD concentration is higher than 125 mg $O_2 \cdot L^{-1}$ (legislation value), so further treatment is needed - Temperatures between 30-55°C can be a drawback	Successfully applied at full scale.
High-solid-content	- Operation temperature around ambient temperature - Moderate-high OLRs	- Slightly high HRT values - COD removal efficiency only between 80-90% - Effluent COD concentration higher than legislative limit. - Post-treatment needed	Future prospects on full scale: nowadays, primary and secondary replacement by AnMBR treatment is not feasible.
Urban	- Very low HRT (lower than industrial) - High SRT (lower than industrial) - High fluxes achieved	- Very low OLR - Very low COD removal efficiency (50-80%) - Effluent COD concentrations far above legislative limit	Lab and pilot scale, full scale applicability still doubtful.

And finally, **the advantages and drawbacks of operating AnMBRs with different parameters or characteristics** can be summarized as:

Table 13. Advantages, disadvantages and drawbacks of operating AnMBR with different parameters and characteristics.

Issue	Advantages	Drawbacks/disadvantages	Remarks
Submerged membrane	- No aeration energy required - Low operation costs - Less biomass stress	- Gas bubbling energy required for fouling prevention - Lower fluxes, so higher membrane area	Submerged membrane fouls easily, so fluxes are lower than external membranes. However, submerged membranes are more used due to low capital and operating costs.
External/side-stream membrane	- Higher TMP, so higher fluxes, so lower membrane area required - Easier membrane cleaning and replacement	- Higher energy costs - Intermediate pump required	
Two-stage configuration	- Optimal operation conditions for each reactor so optimal yields are obtained	- Higher capital costs because of the necessity of 2 reactors	Two-stage configuration tolerates higher loading rates without removal efficiency changes than single-stage configuration.
Multitube module	- Low fouling - Easy handling of SS and viscous liquids - Possibility of membrane replacement	- High capital costs - Low packing density - High pumping costs - High dead volume	The high shear stress can destroy bioflocs and decrease biological activity.
Hollow fiber module	- High packing density - More filtration area per unit volume - Easier cleaning by back-flush operation	- Fouling depends on the hydrodynamics conditions and performance	
Flat sheet module	- Higher permeability - Less cleaning needs - Good stability and replacement	- Lower surface area per unit volume	The mostly used material in IMBR due to the easier membrane replacement

Table 13. (Continued) Advantages, disadvantages and drawbacks of operating AnMBR with different parameters and characteristics.

Issue	Advantages	Drawbacks/disadvantages	Remarks
Inorganic membranes	- High resistance to corrosion, abrasion and fouling	- Expensive	Higher fluxes than polymeric
Metallic membranes	- Better hydraulic performance - Better fouling recovery - Higher tolerance to oxidation and temperature	- Expensive	
Polymeric membranes	- Cheap	- Worse mechanical and thermal properties than metallic and inorganic	The mostly used due to its lower capital costs.
Granulated biomass	- "Gel layer" controllable with cross-flow velocity in EMBR	- More membrane fouling due to its deposition tendency ("Gel layer") - "Gel layer" very problematic in IMBR	Widely used in intensive anaerobic digestion because it avoids biomass washout.
High temperature	- Hydrolysis rate increases leading to higher COD removal - Less VFA accumulation due to methanogens half-rate decreasing.	- EPS production decreases, biomass aggregation also decreases resulting in higher fouling - At thermophilic temperatures, biomass immobilization is more difficult than at mesophilic	
Operating at high fluxes for short time	- Less membrane area required	- Aggressive cleaning damages membrane and reduces its lifetime - The membranes need to be removed offline - Chemical cleaning can last several days, months or years.	
Operating at below "critical flux"	- The physical cleaning can be done more frequently, online and in few minutes	- Low fluxes so more membrane area required	

6. CONCLUSIONS

The main conclusions are:

- AnMBRs present the advantages of membrane bioreactor technology, such as high COD removal efficiency with high effluent quality, low footprint and total biomass retention, with the advantages of anaerobic treatment, such as low sludge production, low energy requirement and the possibility of bioenergy recovery. This fact has made a growing interest in this technology, despite it needs more research for factible application.
- The energy balances have shown that a self-sufficient and energy-producer process is possible with AnMBR technology. Concerning the balances, the limitations (membrane fouling and dissolved methane) must be diminished at maximum level to promote not only a self-sufficient process but economic and energetic feasible process.
- AnMBR technology has been successfully used as industrial wastewater treatment. However, for high-solid-content and urban wastewaters more research is needed to minimize the drawbacks and limitations, in order to comply with regulations and make the applicability feasible.
- The main limitations for AnMBR optimal operation especially for urban wastewater treatment are the membrane fouling issue and the recovery of dissolved methane in effluent. Some methods to diminish fouling have been discovered, but the best optimal method is still under investigation. Concerning dissolved methane recovery, some plausible methods have been successfully used, but more research is needed to implementate the optimal alternative.
- The AnMBR can be and is applied in full scale for industrial wastewater treatment, but for urban wastewaters is still under study (pilot scale), due to low COD removal efficiency, fouling limitation and high dissolved methane which must be optimized.

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