Miguel José Martins Ferreira

Licenciado em Ciências de Engenharia do Ambiente

Design and operational considerations of an Anaerobic Membrane Bioreactor

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Orientador: Engenheiro João Luís Paciência Dinis, CTGA

Co-Orientador: Professora Doutora Leonor Miranda Monteiro do Amaral,
Professora Auxiliar, FCT-UNL

Júri:

Presidente e arguente: Prof. Doutor António Pedro Mano
Vogal: Prof. ª Doutora Rita Maurício Rodrigues Rosa
Vogal: Prof. ª Doutora Leonor Miranda Monteiro Amaral

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Abstract

Anaerobic membrane bioreactor (AnMBR) as a technology has grown as a prominent means of sustainable biological treatment, especially in the recent due to environmental concerns, due to less energy and space requirements, less sludge production, and methane production, which, through cogeneration can make help the system reach energy neutrality. However, membrane cost and the problem of membrane fouling remain the major issues in its widespread use.

Pastry production and the resulting wastewater poses a threat to the environment due to its high biological oxygen demand (BOD) and chemical oxygen demand (COD) concentrations which can result in significant costs on the treatment plant. High organic strength in such wastewater make AnMBR a good choice for its treatment.

This thesis reviews the current state of MBR technology and presents an AnMBR type solution to a large-scale pastry producing facility, while also striving for energy-recovery technologies through cogeneration.

The proposed AnMBR design can theoretically achieve COD removal rates as high as 95% as well as a daily methane production of 2700 Nm^3 or of 3,7 kWh/kg BOD removed;

Keywords: Anaerobic Membrane Bioreactor; Energy recovery, Cogeneration; High organic concentration wastewater

Resumo

Como tecnologia, o reator biológico anaeróbio de membranas tem crescido em popularidade como método de tratamento eficaz. Este apresenta vantagens face a métodos de tratamento convencionais, particularmente no que se refere às preocupações ambientais associadas aos consumos energéticos uma vez que comtempla a produção de biogás sob a forma de metano, que, através de cogeração, pode contribuir para a neutralidade energética do sistema. O AnMBR requer também de menor área de implantação e menor produção de lamas No entanto, os custos associados às membranas bem como o problema da colmatação das mesmas, continuam a ser os principais obstáculos à adoção desta tecnologia a uma escala global.

A indústria pasteleira e os respetivos subprodutos consistem numa ameaça para o ambiente, devido às elevadas concentrações de CBO e CQO, que podem resultar em custos de tratamento significativos para a indústria. Por outro lado, a elevada concentração orgânica deste efluente faz o reator biológico anaeróbio de membranas uma solução ideal para o seu tratamento.

Esta dissertação faz uma revisão ao estado da arte da tecnologia MBR e apresenta uma proposta de um AnMBR como solução para o tratamento de uma indústria pasteleira de larga escala, tentando ainda assim atingir uma taxa de recuperação de energia eficaz através da cogeração.

A estratégia de tratamento proposto através de um AnMBR pode, teoricamente, atingir taxas de remoção de CQO até 95% bem como garantir uma produção de metano até 2700 Nm3 ou 3,7 kWh/kg CQO removido.

Palavras-chave: Reator biológico anaeróbio de membrana; Recuperação energética; Cogeração; Elevada carga orgânica carbónica.

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List of Acronyms

ABR	Anaerobic Baffled Reactor
AMBR	Anaerobic Migrating Blanket Reactor
ANCP	Anaerobic Contact Process
AnCSTR	Continuously Stirred Tank Anaerobic Reactor
ANF	Anaerobic Filter
AnHYB	Anaerobic Hybrid Process
AniMBR	Anaerobic Immersed Membrane Bioreactor
ANL	Anaerobic Lagoon System
AnMBR	Anaerobic Membrane Bioreactor
ANPF	Plug Flow Anaerobic System
AnSBR	Anaerobic Sequencing Batch Reactor
BNR	Biological Nutrient Removal
BOD	Biological Organic Demand
CAS	Conventional Activated Sludge
CFV	Crossflow Velocity
CIP	Cleaning-In-Place
COD	Chemical Oxygen Demand
CSTR	Complete Stirred-Tank Reactor
d	day(s)
EGSB	Expanded Granular Sludge Bed
F/M	Feed to Microorganisms Ratio
FB	Fluidized Bed Reactor
h	hour(s)
HRT	Hydraulic Retention Time
IC	Internal Circulation
LMH	Liter per m2 per hour
MBR	Membrane Biological Reactor

MLSS	Mixed Liquor Suspended Solids
OLR	Organic Loading Rate
SADm	Specific Aeration Demand (membrane)
SRT	Solids Retention Time
SRT	Solids Retention Time
TMP	Transmembrane Pressure
TS	Total Solids
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Blanket
VFA	Volatile Fatty Acids
VLR	Volumetric Loading Rate

1 Introduction

Considering that climate change is one of the most pressing concerns in today's society, efficient and sustainable water use is without a doubt an important goal to strive for.

Water scarcity is a problem that affects a substantial amount of the world's population. Nowadays, two-thirds of the world's population reside in areas that experience cases of water drought at least one month a year. It should be noted that 50% of those affected are from China and India. Worryingly, countries such as Somalia or Libya have 80 to 90% rate of severe water scarcity throughout the whole year (UNESCO, 2017).

Likewise, energy consumption is also a concern, therefore it is important to find and apply technologies that respond to these matters while still providing an effective waste treatment solution.

One technology that answers to these issues is the AnMBR which allows for the effective treatment of wastewater with minimal energy requirements while producing methane, a valuable resource that can be used for energy production.

According to Wozniak, (2012), MBR technology is the fastest growing wastewater treatment system available, with an annual growth rate within 10 and 20%, depending on the country. The spread of the MBR technology has been limited by the prices of the membrane modules, those of which have been decreasing in the recent years as well as improving quality in terms of durability and decreasing energy demand. Nowadays, the energy demand can be around 1kWh/m^3 of water treated in larger plants under optimal process conditions and nominal filtration flux (Lesjean et al., 2011).

In this context, the approach presented here, applied to a pastry industry that chooses to remain unnamed, aims to study the viability on an AnMBR type reactor with a highly efficient treatment outcome as well as a significant methane production which aims to be used in order to reduce operation costs.

Document Structure

This document is structured in seven chapters.

The first chapter includes an introduction to the studied problem.

In the second chapter, a brief presentation of the objectives of this work is made.

The third chapter consists of the literature review. This section contains all the scientific publications and reviews that sustains the claims made in this project.

The fourth chapter is the methodology. In this chapter, the steps and methods used during the elaboration of this work are presented.

The fifth chapter includes the results obtained in this study.

The sixth chapter includes the final conclusions.

The seventh chapter is the final considerations, comments on the limitations of this work as well as indications for further development.

2 Objective

The purpose of this work is to provide a solution for the treatment of the organic waste of a large-scale pastry industry, while aiming to obtain energy recovery through methane production, in a cost-effective manner.

Notably, the study aims to evaluate the implementation of an anaerobic membrane bioreactor to improve the energy balance and reduce the operation costs, while still maintaining adequate treatment.

3 Literature Review

3.1 Comparison between CAS and MBR technologies

Membrane biological reactors (MBRs) have become a solid alternative the conventional activated sludge (CAS) process for the treatment of wastewater, both in the industrial and municipal sectors (Judd, 2010). MBRs are usually favoured over CAS when there are space requirements or a strict treatment is required such as is the case for water reuse. MBRs are able to guarantee the absence of suspended solid (TSS) in the final effluent, which helps the disinfection process (Faisal et al., 2014).

Activated sludge

One of the major differences between MBR and CAS operation is related to the mixed liquor suspended solids (MLSS) concentration in the reactor tank. In the conventional aerated water treatment system, the solids range in the aerator tank can range from 2 to 5 g/L and up to 15 g/L for a basin supplied with a membrane separation technology (Seyssiecq et al., 2008). When considering industrial applications, the total solids (TS) can assume values between 17 and 40.2g/L (Dvořák et al., 2016)

Treatment efficiency

Both MBR and CAS treatment systems use the same biological processes, aerobic or anaerobic, and as such the nutrient removal efficiencies do not differ considerably (Faisal et al., 2014).

Sludge production and handling

Sludge yield in MBR is slightly higher due to total retention of particles and colloids by the membrane. MBRs can be operated at comparatively longer solids retention times (SRT) with higher mixed liquor suspended solids (MLSS) concentration (low F/M ratio) to reduce the sludge production (Faisal et al., 2014).

System footprint

A reduced system footprint is one of the major advantages of the MBR technology. In MBRs, clarifiers, which constitute a large part of the CAS process's footprint, are replaced by the membrane modules which allow for the total retention on suspended solids. That being said, the

MBR can be operated at a higher volumetric loading rate (VLR) by maintaining a high sludge concentration. This allows for a significant reduction of the reactor tank size (Faisal et al., 2014).

Costs

Recent studies have shown that the overall 20-Year-Present-Worth costs of MBR systems are equal to those of CAS systems for plants designed for enhanced nutrient removal or waste reuse. The higher operation and maintenance costs associated with MBR systems is offset by lower capital cost for MBR systems when compared to a traditional CAS treatment plant (Young et al., 2012).

Where treatment requirements are less stringent, or no enhanced nutrient removal is required, MBR systems have a higher capital and 20-Year-Present-Worth operational and maintenance costs than CAS systems (Young et al., 2012).

3.1.1 Anaerobic vs Aerobic Treatment

3.1.1.1 Aerobic

Aerobic treatment is used to remove organic compounds (BOD or COD). This process lacks biological nutrient removal (BNR), unless it includes an anoxic tank, thus providing nitrogen and phosphorous removal.

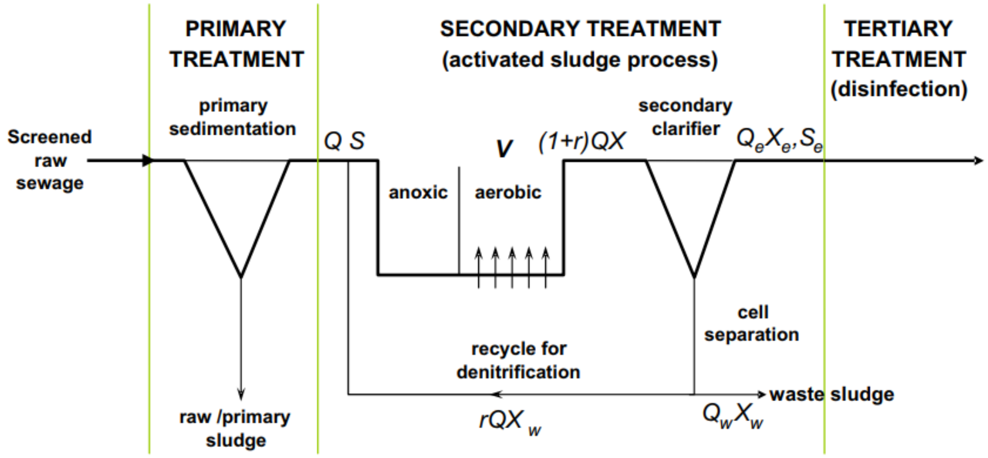

Figure 3.1-1: Conventional sewage treatment process (Judd, 2010).

The conventional sewage treatment process (see Figure 3.1-1) is the combination of screening of gross solids and then sedimentation of settleable solids followed by a biological process. Aerobic water treatment processes may include several configurations such as suspended growth, the conventional activated sludge (CAS) process, or fixed film, predominantly as a trickling filter (TF).

The removal of biological organic demand (BOD) can be obtained by either aerobic suspended growth or attached growth treatment processes. Both depend upon sufficient contact time between the wastewater and heterotrophic microorganisms and sufficient oxygen and nutrients. During the initial biological uptake of the organic material, more than half of it is oxidized, and the rest is incorporated as new biomass, which may be also oxidized by endogenous respiration (Tchobanoglous et al., 2014).

3.1.1.2 Anaerobic

Anaerobic biological reactions involve specialized bacteria that use a variety of electron acceptors in the absence of oxygen for energy production. These are used in a several anaerobic processes in wastewater treatment. These include processes for nitrate/nitrite reduction to nitrogen gases, fermentation processes to produce volatile fatty acids for use in enhanced biological phosphorous removal, anaerobic oxidation of organic compounds in municipal and industrial wastewaters, anaerobic digestion of waste sludge, and anaerobic digestion of other organic wastes (Tchobanoglous et al., 2014).

In high-strength industrial wastewaters, anaerobic treatment has been shown to provide a particularly cost-effective option to aerobic processes with savings in energy, nutrient addition and reactor volume. Because the effluent quality is not as good as that obtained with aerobic treatment, anaerobic treatment is frequently used as a pretreatment step prior to discharge to a municipal collection system or is followed by an aerobic process (Tchobanoglous et al., 2014).

3.2 MBR challenges and future potentials

Technological advances and innovation are typically subject to drivers and barriers which ultimately determine the length of its implementation. It's widely accepted that a major driver for advancement of municipal water and wastewater treatment technology is legislation and that two defining barriers are cost and consumer perception (Emirates & County, 2008)

It has been broadly accepted that MBR technology has a high capital cost. A significant contribution to energy demand is the scouring air requirement of the membrane for maintaining the membrane permeability (Verrecht et al., 2008). This in turn depends on those processes which tend to reduce permeation through the membrane, normally considered to be fouling at the membrane surface (Meng et al., 2009). It is these permeability reduction processes which arguably contribute most significantly to process complexity and robustness, since ameliorating strategies must be developed and imposed to reliably sustain permeability.

A 2011 research paper which looked at a number of studies regarding MBR technology between 1990 and 2009 reached the conclusion that papers related to membrane fouling accounted for 31% of all MBR papers published, as opposed to 1% for papers on clogging and an insignificant number on screening (Santos et al., 2011). The same trend, with focus on fouling was also identified by a survey done on the challenges found by MBR practitioners, where screening and clogging were found to be of most concern and fouling was only considered as being the most important issue by 15% of the respondents. Figure 3.2-1 represents the most problematic topics regarding MBR operation.

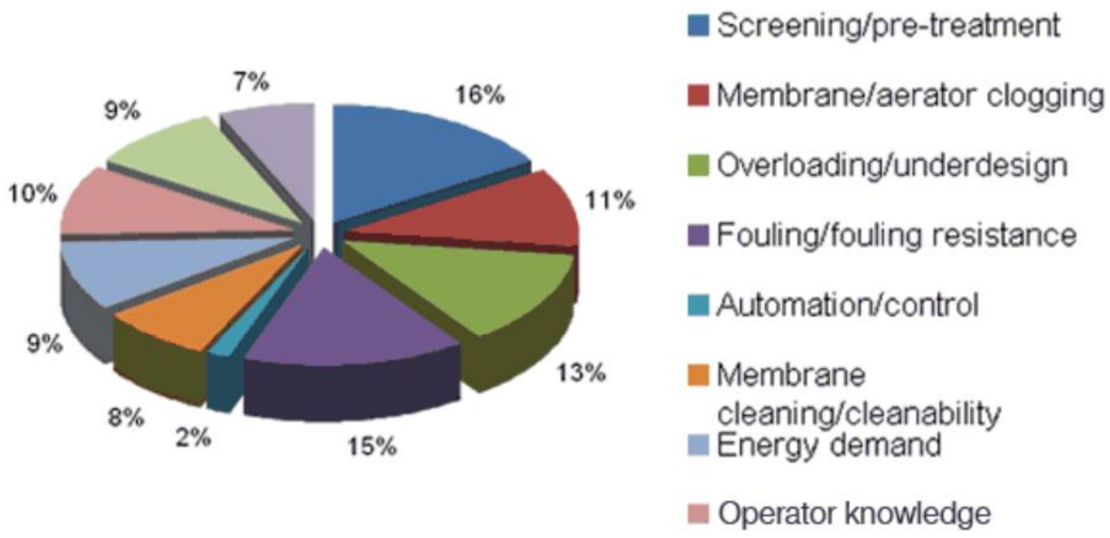

Figure 3.2-1: Analysis of topics identified from the practitioner survey (Judd, 2010).

Despite some of the issues and disadvantages, the MBR technology is now the favorite choice for industrial and often municipal wastewater treatment, especially when advanced treatment is required and/or a compact system is desired (Faisal et al., 2014).

In most countries, continued growth of the MBR market is anticipated, although growth rated vary considerably between countries and/or regions. Currently, the most accelerated growth is observed in China where the MBR market is represented with many different MBR membrane products and technology suppliers (Faisal et al., 2014).

Despite the benefits and drivers, there is still much room for improvement in order to thoroughly utilize the potential of this technology. The more widespread acceptance of the technology as the preferred process over competing technologies essentially depends on further improvement to make it competitive with other technological options. It is likely that a combination of technical advances and the demand for ever improved water quality can sustain, or even increase, the growth in the MBR market to the point where it becomes the default option for wastewater treatment and reuse (Faisal et al., 2014).

3.3 Anaerobic digestion fundamentals

Anaerobic biological reactions involve specialized bacteria and archaea that use a variety of electron acceptors in the absence of molecular oxygen for energy production. They are used in a number of different anaerobic processes in wastewater treatment such as nitrate/nitrite reduction, anaerobic oxidation of organic compounds in municipal and industrial wastewaters, anaerobic digestion of waste sludge, and anaerobic digestion of other organic wastes (Tchobanoglous et al., 2014).

Table 3.3-1 summarizes some of the advantages and disadvantages of anerobic processes compared to aerobic processes. These characteristics don’t make anaerobic processes better than aerobic processes, per se, but it’s safe to say that anaerobic processes exceeds in certain conditions such as when energy consumption is a major concern or environmental conditions such as temperature and pH are easily controlled.

Table 3.3-1: Advantages and disadvantages of anaerobic processes compared to aerobic processes (Adapted from Tchobanoglous et al., 2014).

Advantages	**Disadvantages**
Less energy required	Longer start-up time
Less nutrients required	May require further treatment to meet discharge requirements
Less biological sludge production	Biological nitrogen and phosphorus removal not possible
Methane production	Potential odour production and corrosiveness of gas
Smaller reactor volume	More sensitive to lower temperatures
Potential for lower carbon footprint	May require alkalinity addition

3.3.1 Development and uses

The original engineered anaerobic technologies were created for and applied to the treatment of wastewater. At the time of their development and late 1800s and early 1900s, a community’s wastewater was an unhealthy combination of untreated sanitary wastes, animal manure, and various other local discharges (Tchobanoglous et al., 2014).

Types of Anaerobic Technologies

The major types of anaerobic technologies used for the treatment of wastes are the Low loaded anaerobic lagoon system (ANL), Upflow anaerobic sludge blanket (UASB), Expanded granular sludge blanket (EGSB), Internal circulation UASB (IC), Fluidized bed reactor (FB) Anaerobic contact process (ANCP), Anaerobic filter (ANF), Anaerobic hybrid process (AnHYB), Anaerobic membrane process (AnMBR), Anaerobic baffled reactor (ABR), Anaerobic migrating blanket reactor (AMBR), Anaerobic sequencing batch reactor (AnSBR), Continuously stirred tank anaerobic reactor (AnCSTR) and the plug flow anaerobic system (ANPF). The present study will focus particularly on the AnMBR, a mixed reactor system using suspended/flocculating anaerobic biomass and synthetic membrane solids-liquid separation with solids recycle to provide a long SRT with the short hydraulic retention time. The AnMBR is designed for a COD loading rate of 5 to 15 kg/m^3.d (Tchobanoglous et al., 2014).

3.3.2 Microbiology and chemistry

The anaerobic degradation pathway of organic matter is a multi-step process of series and parallel reactions. This process of organic matter degradation can be subdivided into four successive stages, namely: hydrolysis, acidogenesis, acetogenesis and methanogenesis. In Figure 3.3-1, a scheme for the anaerobic digestion of polymeric materials is described, representing the interactions between each step and sub product where the numbers indicate the bacterial groups involved: 1. Hydrolytic and fermentative bacteria, 2. Acetogenic bacteria, 3. Homo-acetogenic bacteria, 4. Hydrogenotrophic methanogens, 5. Aceticlastic methanogens

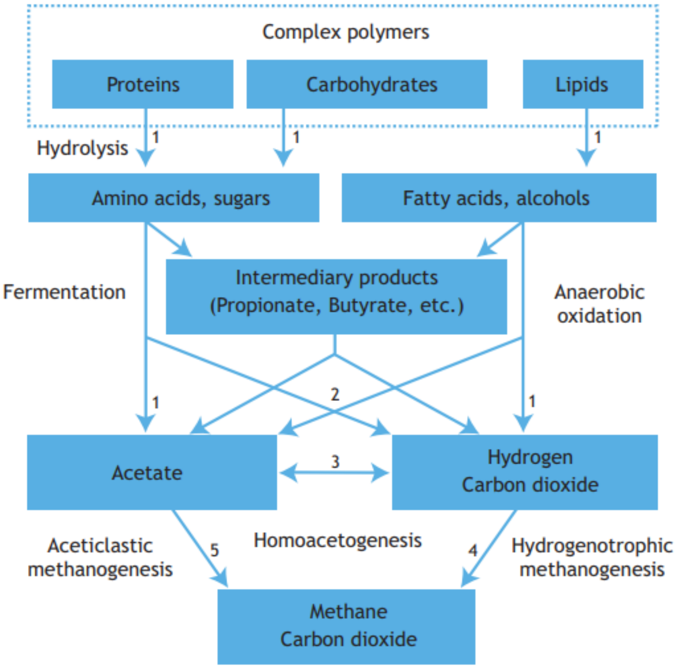

Figure 3.3-1: Reactive scheme for the anaerobic digestion of polymeric materials Gujer and Zehnder (1983).

3.3.2.1 Hydrolysis

This step is where enzymes excreted by fermentative bacteria convert complex, undissolved material into less complex, dissolved compounds which can pass through the cell walls and membranes of the fermentative bacteria (Henze et al., 2008).

Since bacteria are unable to take up particulate organic matter, the first step in anaerobic degradation consists of hydrolysis of polymers. This process is merely a surface phenomenon in which the polymeric particles are degraded through the action of enzymes to produce smaller molecules which can cross the cell barrier (Henze et al., 2008).

3.3.2.2 Acidogenesis

This is where the dissolved compounds present in cells of fermentative bacteria are converted into a number of simple compounds which are then excreted. The compounds produced during this phase include volatile fatty acids (VFAs) alcohols, lactic acid, CO_2, H_2, NH_3 and H_2S as well as new cell material (Henze et al., 2008).

Acidogenesis is the most rapid conversion step in the anaerobic degradation. For that reason, anaerobic reactors are subject to souring, i.e. a sudden pH drop, when reactors are overloaded or perturbed by toxic compounds. This inhibits methanogenesis.

3.3.2.3 Acetogenesis

Acetogenesis is where digestion products are transformed into acetate, hydrogen and CO_2 as well as new cell material (Henze et al., 2008).

The growth rate of aceticlastic methanogens is very low, resulting in doubling times of several days or more. These extremely low growth rates explain why anaerobic reactors require a very long start-up time with unadapted seed material and why high sludge concentrations are pursued.

3.3.2.4 Methanogenesis

This is where acetate, hydrogen and carbonate, formate or methanol are converted into methane, CO_2 and new cell material.

During this stage, methanogenic bacteria convert hydrogen and acetic acid to methane and carbon dioxide. Methanogenesis is affected by conditions in the reactor such as temperature, feed composition and organic loading rate (Parawira, 2004).

The product of this stage, biogas, consists mainly of methane (CH_4) and carbon dioxide (CO_2), but also includes several other gas-state “impurities” such as hydrogen sulfide, nitrogen, oxygen and hydrogen. Biogas with a methane content higher than 45% is flammable; the higher CH_4 content the higher the energy value of the gas (Steinhauser & Deublein, 2011).

3.4 AnMBR technology

Whilst almost all MBR technologies implemented are aerobic, there has been an increase of interest in anaerobic MBRs since the mid-2000s. The technology provides the potential for removing COD with a net energy benefit from the methane generated, albeit without nutrient removal. Whilst the sidestream configuration (AnsMBR), namely the product called *Memthane*, was originally commercialized in the early 1990s and is still provided by at least one multinational company, the most recent interest has been associated with the immersed configuration (Judd, 2014).

The anaerobic membrane bioreactor (AnMBR) technology appeared to be the suitable emerging technology. Membrane costs have decreased significantly (Krzeminski et al., 2017), therefore, the technology has gained in popularity for the treatment of both low- and high-strength wastewater. This is mainly due to the fact that AnMBR has the ability to provide superior effluent quality for reuse and a reduced operational footprint (Ozgun et al., 2013) and nutrient recovery compared to an conventional anaerobic treatment that depends on gravitational settling. The AnMBR process proved to be a solid technology in tourist areas and public places for wastewater treatment.

However, membrane fouling continues to be a primary challenge to the spread of the AnMBR system (Gao et al., 2011) because of its direct effect on capital and operating costs (Feng et al., 2011).

Available information suggests that AnsMBRs can provide a COD degradation 99% or more, the percentage of removal increasing with increasing feedwater concentration, and achieve a flux of 15-30 LMH for a range of food effluent applications. Operating conditions such as crossflow velocity (CFV) and transmembrane pressure (TMP), when reported, appear to be similar to those employed for an aerobic sMBR, with a reduction in the CFV producing a corresponding reduction in the sustainable flux (Judd, 2010). This being the case, the value offered by anaerobic as opposed to aerobic treatment by an sMBR is determined by the balance of (from the perspective of the anaerobic option):

1) The OPEX benefit of the methane generated, which is then proportional to the difference in the feed and permeate COD concentration;
2) The OPEX benefit of the reduced process aeration (assuming all other aspects of the anaerobic and aerobic biological process OPEX to be similar);
3) The OPEX benefit of the reduced sludge production;
4) The OPEX penalty of the increased specific energy demand for the membrane filtration (which is proportional to the flux);

5) The CAPEX penalty associated with the larger membrane area demanded by the lower flux;
6) The overall cost penalty of supplementary downstream nutrient and residual COD removal, if required.

Since flux does not appear to be a function of loading, the anaerobic MBR option – as with the classical treatment – becomes more viable at higher loadings. This arises from a combination of the calorific value (CV) of the methane generated (1) and the reduction in process aeration (2), both of which are roughly linearly related to the COD (as is the proportional reduction in sludge (3)). The OPEX penalty (4), for a pumped sMBR, roughly equates to the permeability, whereas the CAPEX penalty is inversely proportional to the flux (Judd, 2014).

It is because of the significant OPEX penalty that there has been recent interest in the immersed configuration (aniMBR) which, as described in chapter 3.4.2, follows the same configuration as a submerged MBR where the filtration unit is immersed in the mixed liquor. This technology demands a much-reduced energy for permeation and for which scouring can potentially be provided by the generated biogas. Pilot-scale studies of this configuration, along with data from a full-scale installation, suggest that aniMBR fluxes are generally in the range of 4-10 LMH (Dereli et al., 2012) depending on the feedwater quality. There is also some indication from iHF studies that backflushing may significantly increase the sustainable flux (Judd, 2014).

Anaerobic MBR treatment is normally only viable at very high COD concentrations (15-250 g/L) when the recovered methane generated by anaerobic degradation of the organic matter provides a significant cost benefit. The latter may then offset the increased costs associated with low flux operation (15-30 LMH), the longer residence times (necessitating a larger bioreactor), and the requirement for a sealed system (Judd, 2014).

3.4.1 Operations, conditions and parameters

The common operational parameters that are monitored are hydraulic retention time (HRT), solids retention time (SRT), temperature, pH and F/M ratio, VFAs and alkalinity are also considered.

3.4.1.1 HRT and SRT

The HRT and SRT are two of the most important parameters when it comes to MBR performance. On one hand, longer HRT will require larger space requirements (Smith et al., 2012). On the other hand, shorter HRT will cause higher MLSS concentration in the reactor tank due to higher OLR (Huang et al., 2011). Usually an SRT of more than 20 days is applied to anaerobic wastewater treatment at 30 ºC, and higher SRT is required for lower temperatures (Tchobanoglous et al., 2014).

3.4.1.2 Temperature

Due to slow growth rates in anaerobic systems, temperature is a crucial parameter that must be carefully controlled in order to maintain the microorganism's growth rate as well as their performance.

3.4.1.3 pH

The acceptable range of pH for methanogens is generally 6.8 to 7.6 (Kang et al., 2002). A pH value outside this range will have an adverse effect on the process efficiency, and the system may take several weeks or months to recover. Maintaining the pH at 6.8 is also difficult in some circumstances since due to the intermediate organic acids produced during the start-up, overload or unsteady periods, can lower the pH and hinder methane production.

3.4.1.4 F/M

F/M is a controllable parameter that can significantly influence system performance. A higher F/M value results in higher amounts of EPS, SMP and fine particles in a system, and accelerates membrane fouling in AnMBRs (Liu et al., 2012).

3.4.2 Configurations

Different configurations determine the membrane's geometry and their relative position to the liquid's flux. These affect the whole filtration process and should be carefully considered in order to maximize shear, cleaning ability and modularity, as well as minimizing fouling and membrane costs.

There are six principal configurations currently employed in membrane processes, which all have various practical benefits and limitations, as detailed in Table 3.4-1. The configurations are based on either a planar or cylindrical geometry:

1. Plate-and-frame/flat sheet (FS)
2. Hollow fibre (HF)
3. (Multi)tubular (MT)
4. Capillary tube (CT)
5. Pleated filter cartridge (FC)
6. Spiral-wound (SW)

Table 3.4-1 - Membrane configurations (Adapted from Judd, 2010).

Configuration	Turbulence Promotion	Backflushable	Application
FS	Fair	No	DE, UF, RO
HF	Very poor	Yes	MF, UF, RO
MT	Very good	No	MF, UF, high TSS waters, NF
CT	Fair	Yes	UF
FC	Very poor	No	MF, low TSS waters
SW	Poor	No	NF, UF, RO

DE = Dead-end, UF = Ultrafiltration, RO = Reverse osmosis, MF = Microfiltration, NF = Nanofiltration

For the reasons previously outlined, only FS, HF and MT configurations are suitable for MBR water treatment technologies. These modules allow for turbulence promotion and regular effective cleaning. Turbulence can originate from either passing the feedwater or an air/water mixture along the surface of the membrane to facilitate the transfer of permeate through it.

Physical cleaning can be achieved by reversing the flow (backflushing) at a rate 1 to 3 times higher than the regular flow in an attempt to dislodge some of the fouling layer on the retentate side. The membrane must be sufficiently resistant in order to withstand the hydraulic stress caused by the inversion of the flow’s direction. For this reason, backflushing ability is limited to HF and CT membrane types (Judd, 2010).

3.4.2.1 External cross-flow

Based on the relative location between the anaerobic bioreactor and membrane module, membrane configurations could be divided into the submerged (including internal and external submerged) and side-stream types (Liao et al., 2006; Shoener et al., 2016; Smith et al., 2012). The main difference is that in the submerged configuration, the membrane module is directly installed into the bioreactor (internally or externally), with the membrane being operated under vacuum (Ersahin et al., 2014), whereas for the side-stream configuration, the membrane module is located outside the bioreactor in an additional membrane tank and the membrane is operated under pressure (Alibardi et al., 2016). Conventional AnMBR studies have reported that gas sparging energy and cost of a submerged membrane are approximately three times lower compared to the side-stream AnDMBR for a given flux (Ersahin et al., 2017; Jeison & van Lier, 2006). Moreover, the energy demand per permeate flow volume for submerged configurations was much lower than that for pumped side-stream configurations in AnMBRs (Martin-Garcia et al., 2011). Such MBR configuration is shown on Figure 3.4-1.

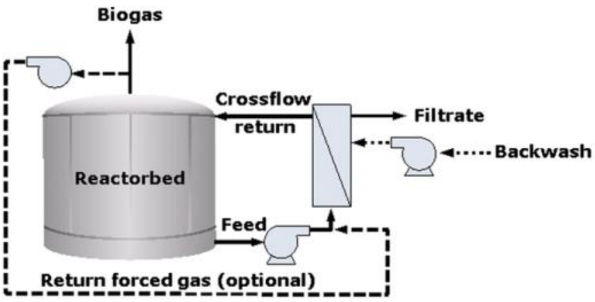

Figure 3.4-1: External crossflow AnMBR configuration (Judd, 2010).

3.4.2.2 Internal submerged

This type of membrane configuration is very common due to its compatibility with the already existing activated sludge process, as the membrane module can be directly immersed into the reactor vessel as shown in Figure 3.4-2.

Due to their low space requirments, low energy demand and easy sludge wasting directly from the reactor, internal MBRs have become a very popular option but they are most suitable for wastewater with good filterability and require a higher membrane area for effective treatment (Faisal et al., 2014).

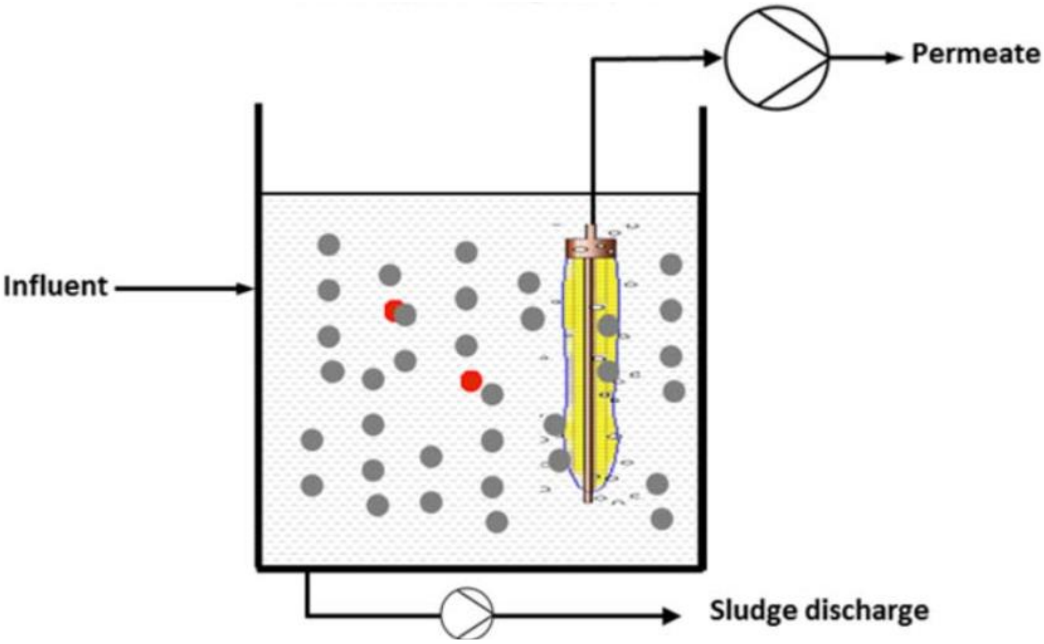

Figure 3.4-2: Schematics of internal submerged MBR (Faisal et al., 2014).

3.4.2.3 External submerged

In this type of MBR, the membrane modules are placed outside the reactor tank, as show in the Figure 3.4-3. In this arrangement, the mixed liquor from the reactor is pumped into the exterior membrane module. External MBR are primarily used in industries as these require less membrane area compared to submerged type MBRs. However, these require higher energy demands due to the pumping and sludge recirculation requirements; they also need have higher space requirements (Faisal et al., 2014).

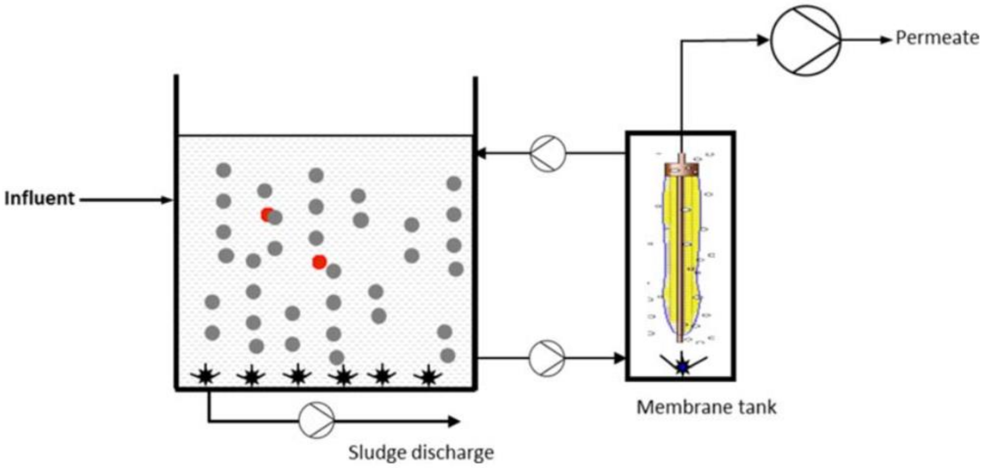

Figure 3.4-3: Schematics of external submerged MBR (Faisal et al., 2014).

3.5 Fouling

Membrane fouling is regarded as one of the most challenging issues that restrict the widespread use of AnMBR technology. It results in a reduction of permeate flux or an increase in transmembrane pressure (TMP), reduced productivity and increased operating costs (e.g., added energy consumption, increased membrane cleaning and replacement cost) (Faisal et al., 2014)

In comparison to aerobic MBRs, there are a limited number of studies that have been conducted on the fouling of AnMBRs. In one particular review study (Skouteris et al., 2012) concluded that membrane fouling in AnMBRs is more severe than in aerobic MBRs because of lower sludge filterability.

The different levels of fouling present in aerobic and anaerobic MBRs may be attributed to the fact that the sludge characteristics and biological activities in anaerobic and aerobic systems are not the same. Under aerobic conditions, sludge is produced at a high growth rate. Anaerobic sludge mainly originates from its low biomass yield and influent particulates (Judd, 2010).

Summarizing, Lin et al., (2012) concluded that more attention should be paid to membrane fouling control in MBRs treating industrial wastewaters. However, a unified and well-structured theory on membrane fouling is not currently available because of the inherent complexity of the system (Faisal et al., 2014).

3.5.1 Classification of fouling

3.5.1.1 Removable and irremovable fouling

Membrane fouling is a very complicated phenomenon and results from multiple causes. As seen in Figure 3.5-1, reasons for permeability decline are not all the same and can be classified according to the type of fouling.

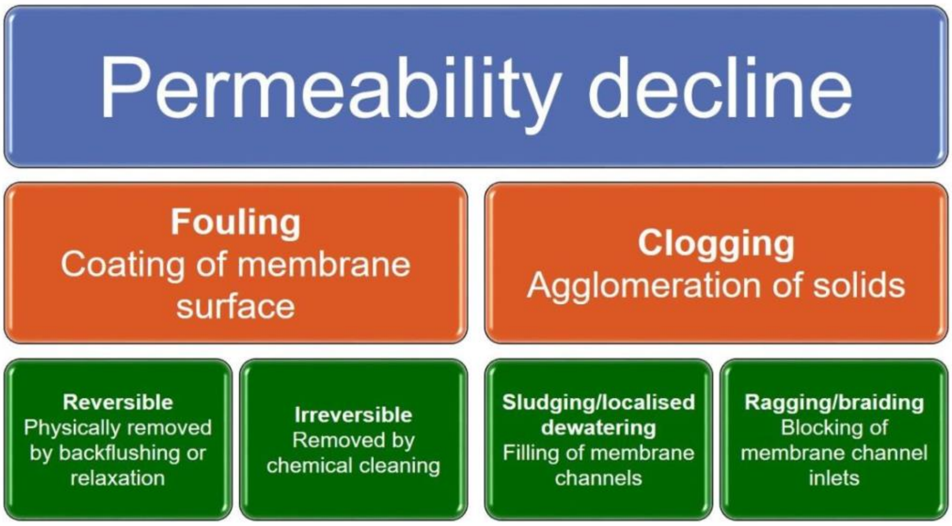

Figure 3.5-1: Reasons for permeability decline (Adapted from http://www.thembrsite.com/features/when-sludge-goes-bad-may-2010/)

Particle sizes of sludge flocs, colloids and solutes in mixed liquor may strongly affect fouling mechanisms in a membrane filtration system. If foulants are comparable with the membrane pores (i.e. solutes), adsorption on pore wall and pore blocking may occur. However, if the pollutant (i.e., sludge flocs and colloids) are much larger than the membrane pores, they tend to form the so-called cake layer on the membrane surface (Meng et al., 2009).

In past scientific literature, has been some confusion with different definitions of reversible and irreversible fouling. Kraume et al (2009), defines three types of fouling: removable fouling, irremovable fouling and irreversible fouling. As shown in Figure 3.5-2, the removable fouling is the one that can be easily eliminated by implementation of physical cleaning (e.g. backwashing), while irremovable fouling needs chemical cleaning to be eliminated. The concepts of removable fouling and reversible fouling are the same. Generally, removable fouling is attributed to the formation of cake layer, and the irremovable fouling is attributed to pore blockage (Meng et al., 2009).

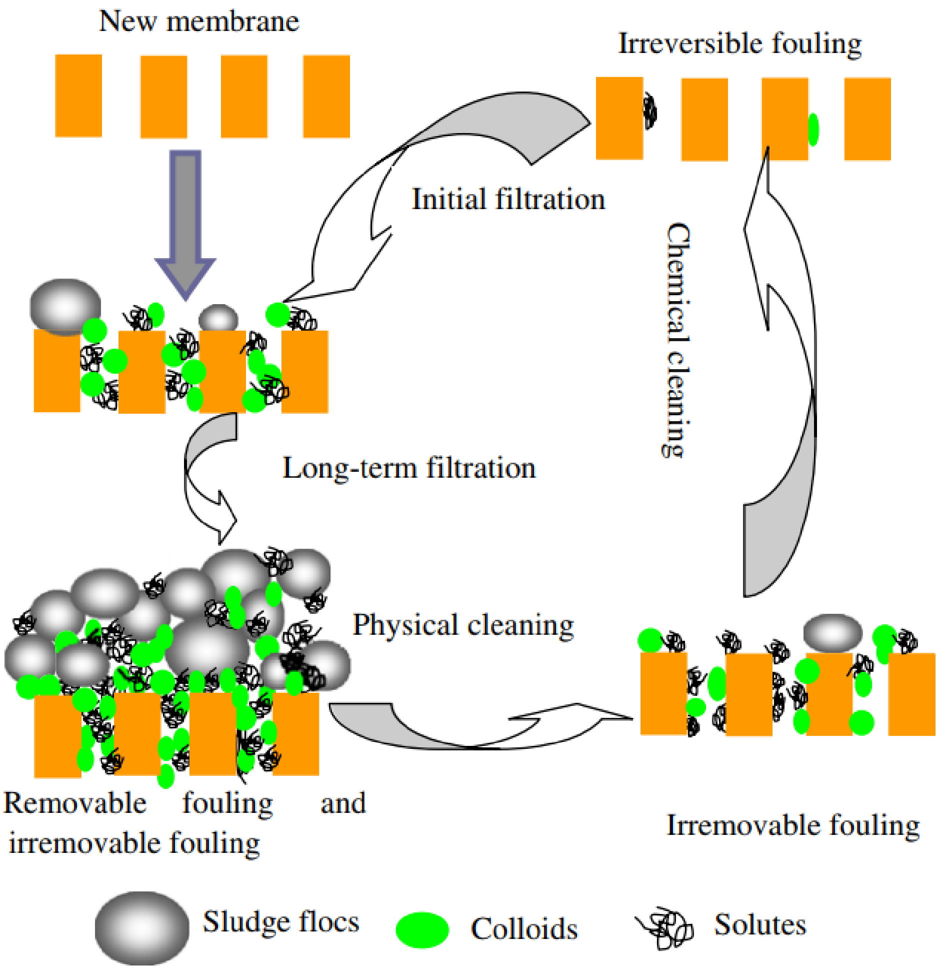

Figure 3.5-2: Schematic illustration of the formation and removal of fouling in MBRs (Meng et al., 2009).

3.5.1.2 Biofouling, organic fouling, and inorganic fouling

From the viewpoint of fouling components, the fouling in MBRs can be classified in three major categories: biofouling, organic fouling and inorganic fouling.

Biofouling refers to the settling, growth and metabolism of microorganisms of bacteria cells or flocs on the membrane surface. For low pressure membranes such as microfiltration and ultrafiltration for the treatment wastewater, biofouling is a major problem because most foulants in MBRs are a lot larger than the membrane pore size (Pang et al., 2005; Wang et al., 2005).

Organic fouling in MBRs refer to the deposition of biopolymers such as proteins or polysaccharides on the membrane surface. These foulants are small in size, therefore they can be deposited onto the membrane more quickly due to the permeate flow, but they have lower backflush transport velocity compared to large particles such as colloids and sludge flocs which get detached easily (Meng et al., 2009).

Inorganic fouling is the least common type of fouling compared to biofouling and organic fouling, although all of them take place simultaneously during membrane filtration of activated sludge. Kang et al., 2002 investigated a filtration system where a layer of struvite was found in the membrane. They found that high alkalinity could be the reason for the precipitation of CaCO3. More recently Wang et al. 2008b observed that the cake layer included inorganic elements such as Mg, Al, Fe, Ca, Si, etc. Due to the difficulty of removing such foulants, this type of fouling is possibly avoided by pretreatment of the feedwater and/or implementation of previous chemical cleaning (Meng et al., 2009).

3.5.1.3 Ragging or braiding

In the case of municipal wastewater treatment, the problem of clogging of membrane pores and channels by large particles in the MBR module is aggravated by their apparent tendency to agglomerate into “rags” or “braids” up to 1 meter in length, as seen in Figure 3.5-2. These rags appear to be made up primarily of cellulosic fibers, supposedly from bathroom tissues and hairs. Such extensive agglomeration is may collect at the channel entrances and (see Figure 3.5-1, picture b), this is referred to as “matting”. In some cases, rags may agglomerate at the membrane aerator, which is extremely detrimental to the treatment process since clogging rapidly ensues without scouring of air to properly displace the solids from between the membranes (Judd, 2010).

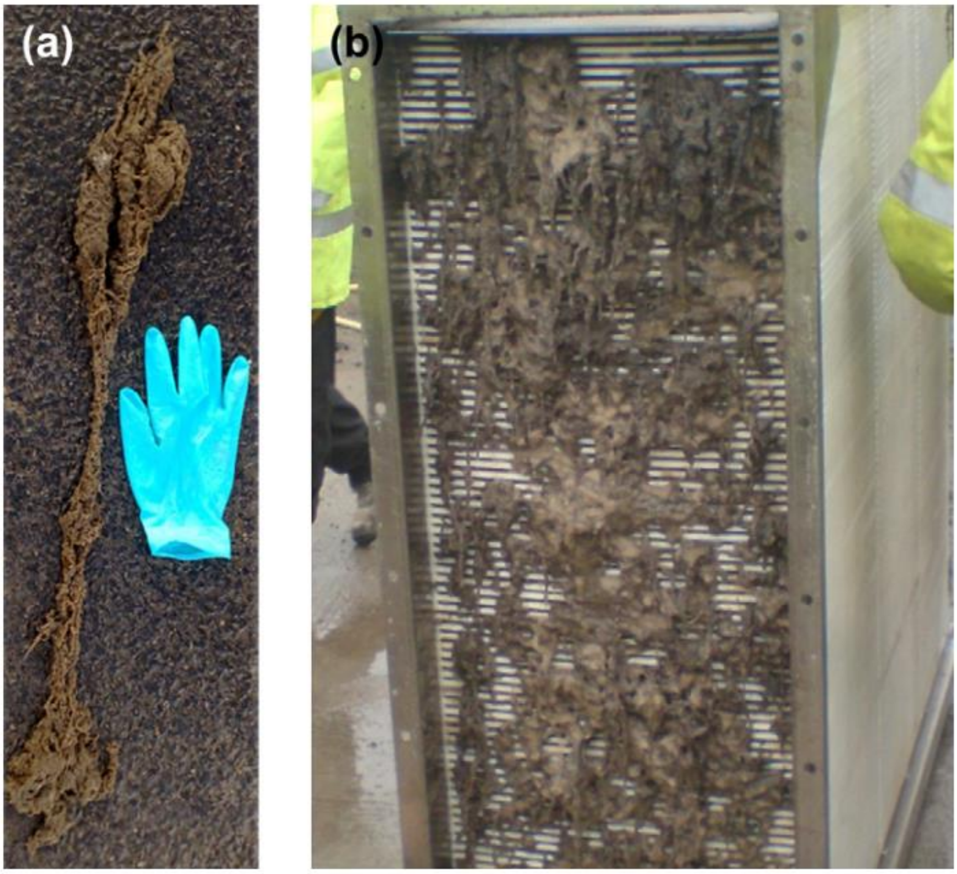

Figure 3.5-3: (a) An 80 com "braid" and (b) "braiding"/"matting"/"ragging" of membrane channel entrances in a flat sheet module (Judd, 2010).

3.5.2 Fouling control

Screening

Screening is broadly accepted as being essential in suppressing clogging of the membrane modules. While the standard rating at the inlet of a conventional sewage treatment is 6 mm, for an MBR the rating ranges from 3 mm to 1 mm or less. The quantities of the screening generated in an MBR process are therefore considerably greater than that produced by classical sewage treatment, and the management of this waste should be taken into consideration (Judd, 2010).

3.5.2.1 Chemical approaches

Despite its several disadvantages such as transportation, storage, preparation and the production of secondary contaminants, chemical cleaning has been the primary tool used to restore membrane permeability (Le-Clech et al., 2006).

As stated before, reversible fouling caused by the deposition of sludge flocs can be prevented by using sub-critical flux operation or physical cleaning such as backwashing, air scouring and so on. The irreversible fouling, caused by adsorption and/or chemical bonding between membrane surface and foulants cannot be managed by optimizing the flux conditions or other physical cleaning methods. Therefore, periodical chemical cleanings are required in full scale MBR treatment plants. Chemical cleaning is carried out in two ways: off-line cleaning and cleaning-in-place (CIP). Off-line cleaning, the membrane modules are taken out of the bioreactor and immersed in a separate tank containing a cleaning agent. In CIP, chemical agents are added directly into the membrane in a reserve flow while membranes are still submerged in the bioreactor (Faisal et al., 2014).

Compared to off-line cleaning, CIP is the simpler and cheaper alternative (Gao et al., 2011). The periodic automatic CIP cleaning, also known as “maintenance cleanings”, normally use a combination of NaOCl for the removal of organic polymers through oxidation, as well as mineral and/or organic acids for dislodging scales and metal oxides (Judd, 2010). Occasionally CIP also takes form as a chemically enhanced backflush, where the chemicals are added to the backflushing water to enhance foulant removal (Zsirai et al., 2012). NaOCl used is chemical cleanings in MBR technology typicially varies in concentration from 1000 to 3000 mg/L (Faisal et al., 2014).

3.5.2.2 Physical approaches

Aeration

An excessive and extensive aeration to a MBR tank is the most widely practiced way to vibrate the submerged membrane mechanically and dislodge the sludge foulants on the membrane. Unfortunately it requires large amounts of energy (Judd, 2008).

Backflushing

Backflushing or backwashing has been considered as the main tool for the control of reversible fouling in most membrane filtration processes, including MBR technology. This cleaning technique is usually done with permeate, clean water with or without the use of cleaning chemicals. The main disadvantage of backflushing is that, over a long period of time, it can cause membrane disintegration, so that the life span of a membrane should be considered first for backflushing.

Critical flux

After the critical flux concept was introduced by Field et al., (1995), sub-critical flux operation in membrane processes has been practiced commonly for the purpose of retardation of severe membrane fouling. In other words, by operation at a lower flux, the fouling process will be significantly retarded while still maintaining effective filtration results.

According to Tchobanoglous et al., (2014), there are several types of membrane fouling, which depend on the wastewater's constituents and affect the membrane's performance as shown in Table 3.5-1.

Table 3.5-1 - Typical wastewater constituents that cause membrane fouling and membrane damage (Adapted from Tchobanoglous et al., 2014)

Type of fouling	Responsible wastewater constituents	Remarks
Particulate fouling	Colloids Oils Clays and silts Iron and manganese oxides Powdered activated carbon	Can be reduced by cleaning the membrane at regular intervals.
Scaling	Barium sulphate Calcium carbonate Calcium fluoride Calcium phosphate Silica	Can be reduced by limiting salt content, pH adjustment and by the addition of antiscalants.
Membrane damage	Acids Bases pH extremes Free oxygen Free chlorine	Depends on the selected membrane. Limited by controlling the amount of these substances.
Organic fouling	Natural organic matter Fulvic acids Humic acids	Effective pre-treatment should be used to prevent organic fouling.
Biofilm fouling	Microorganisms	Biofilm is formed on the membrane surface by colonizing bacteria.

3.6 AnMBR for the treatment of high strength wastewaters

Industrial wastewater treated by AnMBR include effluent from food processing, pulp and paper, tannery, chemical, pharmaceutical, textile, petroleum and manufacturing industries. These are generally characterized by high organic strength with relatively high solids concentration. Effluent from food processing industries are readily biodegradable, non-toxic, and they fit exactly on in the “high organic strength, highly particulate” category of wastewater, deemed by Liao et al., (2006) as the most suited for treatment by AnMBRs.

On average, COD removal efficiency in treating industrial wastewater was over 90%, with applied organic loading rates (OLR) ranging from 2-15 kg COD/m^3/day. Because most of the AnMBRs use a complete stirred-tank reactor (CSTR) configuration, this OLR range may seem lower than what can be achieved with the high rate anaerobic reactors such as the UASB or EGSB. These are, however, higher than the conventional CSTR digesters (Liao et al., 2006).

Wastewater with extreme characteristics, chemical and toxic contaminants can also be treated with AnMBR, given the appropriate auxiliary or pre-treatment steps in place. Fischer-Tropsch process wastewater, a typical petrochemical wastewater with high strength and low pH that consists of short chain organic acids was treated by AnMBR achieving effluent COD of less than 500 mg/L and an OLR up to 25 kg COD/m^3/day, while fixed media systems proved to be a failure (Lin et al., 2013).

AnMBR has also been successfully tested for the treatment of meat processing/slaughter house effluent, palm oil mill effluent and cheese whey (Stuckey, 2012). As a wastewater of high organic strength, effluent from meat processing plants and slaughterhouses is considered to be highly suited for treatment by anaerobic processes (Nacheva et al., 2011)

4 Methodology

4.1 Case study

4.1.1 Introduction

For the development of the present study, an unnamed pastry industry was chosen as a case for the hypothetical implementation of an anaerobic MBR treatment system with significant energy benefits and water treatment capacity.

For privacy reasons, this industry will remain unnamed.

4.1.2 Study

The objective of this study was the characterization, both quantitative and qualitative, of the organic waste produced in this pastry industry. This pastry waste was considered for the production of energy, through anaerobic co-digestion in conjunction with the rest of the wastewater produced by this industrial facility.

The data hereby presented was collected both *in situ* and through email communication with the industry themselves.

4.1.3 Wastewater and organic waste characterization

4.1.3.1 Wastewater characterization

The following table contains the average characterization of the wastewater produced by the pastry industry.

Table 4.1-1: Wastewater characterization.

PARAMETER	UNIT	VALUE
Daily Average Flow	**m^3/d**	83
BOD	**Kg/day**	3600
COD	**Kg/day**	6100
TSS	**Kg/day**	2600
Temperature	**ºC**	> 15
pH	**Sorensen**	3,5 to 5,0

4.1.3.2 Organic waste characterization

Through its regular production activity, this industry generates considerable amounts of solid pastry waste, such as fresh pastry, products rejected by quality control, expired products, returns, etc. It has been estimated that in the past year, approximately 3100 tons of organic waste was produced (approximately 8.5 Ton/day, in average).

According to the information given by the industry, these pastry products can be characterized by their abundance in carbohydrates, lipids and proteins. For the purpose of this case study, it was considered the following average composition for these waste products: 50% carbohydrates, 9% lipids, 8% protein and 3% fiber. It was assumed that the waste had a water content of 30%, which is in line with the usual values for pastry related wastes.

4.1.4 Organic waste energy recovery

4.1.4.1 Introduction

The following chapter aims to cover the hypothetical solution that considers the organic waste energy recovery using the by-products of this pastry production facility.

The studied solution considers the co-digestion of the solid organic waste with the industrial wastewater in an anaerobic digestor operated in mesophilic conditions.

4.1.4.2 Organic waste co-digestion

Before being used for anaerobic digestion, the organic waste by-products will be properly prepared (separated from their packaging, shredded, homogeneously mixed, etc.) and dissolved together with the raw industrial wastewater, which come from the IWWTP’s equalization tanks.

If necessary, the mixture will be pH and alkalinity corrected, therefore establishing the optimum conditions in nutrients for anaerobic digestion.

After providing adequate conditioning, the wastewater and solid waste mixture will be forwarded to anaerobic digestion, through pumping.

The foreseen anaerobic treatment, which consists in a completely mixed anaerobic bioreactor, operated in mesophilic conditions, will provide a significant reduction in the organic matter content in the wastewater. In highly biodegradable wastewater, such as it is expected in this industrial pastry facility, due to its nature, its assumed to achieve COD removal rates equal or above 90-95%, as long as the adequate environmental conditions for the growth of anaerobic bacteria are provided and there isn’t a high percentage of dissolved organic matter present.

Anaerobic digestion, regardless of the type of waste to be treated and the technology used, is entirely dependent on the biological processes such as the microbiological decomposition of organic matter in anaerobic conditions. During anaerobic digestion, organic matter is converted in methane, carbon dioxide and biomass.

Generally, anaerobic systems have one or more of the following objectives:

- Elimination of biodegradable organic compounds;
- Sludge stabilization;
- Enhancing sludge dewatering characteristics;
- Better energy recovery from methane production.

Anaerobic digestion has been declared as a competitive treatment technology, particularly in the last decades. Most types of wastewater containing high levels of biodegradable organic matter can be subject to high performance anaerobic processes. In countries like the Netherlands, almost all agro-industrial wastewater is treated is actually treated using anaerobic systems.

Anaerobic digestion offers several advantages when compared to conventional aerobic treatment, such as:

- Significantly reduced energy consumption;
- Up to 90% lower biological sludge production;
- Energy recovery using methane, with a theoretical yield value of 3,7 kWh/kg BOD removed;
- Low or non-existent chemical reagent requirements;
- Relatively simple technology, but still maintaining a high treatment efficiency, regarding carbon based organic matter;
- Relatively fast start-up, when using anaerobic sludge as inoculum.

Aerobic systems are, in fact, slightly more efficient than anaerobic ones but operating costs are, in average, three times higher in the aerobic system, particularly when it comes to energy costs related to aeration. Still, initial investment costs are, generally, in the same order of magnitude.

Thus, when its necessary to achieve high carbonated organic matter removal efficiencies, while keeping operating costs down, anaerobic digestion in mesophilic reactor conditions becomes one of the best treatment solutions available on the market on the condition that the waste products are already warm.

In general, the treatment process is extremely robust and is capable of producing a high-quality effluent with high stability (with low COD and BOD concentrations) among a variety of environmental conditions and with minimal human intervention necessary.

The high sludge age that will occur in the system will lead to a high degree of biomass adaptation, increasing the stability of the process and high rates of gas production.

4.1.4.3 Digestate adjustment

After anaerobic digestion, the resulting digestate must be subjected to further treatment before discharge in the municipal sewage system. According to the digestate characteristics presented previously, the case study pastry facility has sufficient capacity to ensure the fulfillment of the legal required discharge values by the local municipality.

4.1.4.4 AnMBR configuration

An external submerged MBR system allows for improved chemical cleaning and lowers fouling conditions. This results in better control over clogging and foaming; the environmental conditions of the anaerobic biological reactor can be operated and optimized independently with no fluctuations, dead zones and short circuits, therefore resulting in better effluent quality. This type of MBR arrangement require less membrane area, therefore less initial investment costs and work better for high strength wastewater with poor filterability (Faisal et al., 2014).

Figure 4.1-1 shows a simple diagram representing the external submerged membrane configuration.

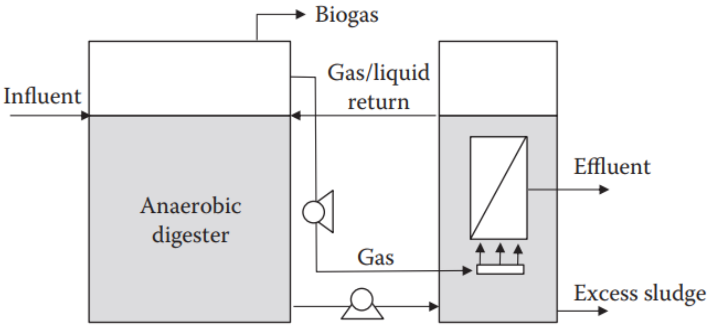

Figure 4.1-1: External submerged membrane process diagram (Judd, 2010).

Table 4.1-2: Design Parameters of AnMBR for industrial wastewater (Kang et al., 2002).

Design parameter	Range	Unit
Temperature	30 - 40	ºC
pH	6.8 - 7.6	-
F/M	< 0.4	kg COD/MLVSS/d
F/V	3 to 6	kg COD/m^3/d
MLSS	6 to 15	g/L
Y_{obs}	0.04-0.05	g MLSS/g COD
Flux	3 - 7.5	LMH
Gas sparging	0.2 - 0.3	m^3/m^2/h
Specific energy demand	0.5 - 1.5	kWh/m^3

4.1.5 CAPEX and OPEX

There are two main categories of capital expenses, namely:

- ***CAPEX*** – Capital expenditure. This acronym is used for the capital used to acquire physical goods, such as equipment and infrastructures.
- ***OPEX*** – Operational expenditure. This concept represents the capital used to maintain and operate the existing equipment and infrastructures.

Both these concepts are interdependent. A reduction in *CAPEX* values is usually associated with an increase in *OPEX*, and vice-versa (Fletcher et al., 2007).

Applying these concepts to MBR, the *OPEX* is associated with the membrane's operational costs such as energy, cleaning reagents and operational maintenance. The *CAPEX* represents everything else, including construction works and equipment acquisition. Based on this information, it's safe to assume that the most expensive treatment plants produce the lowest operational costs since they implement design elements that, while individually more expensive, are more efficient in the long-term (Fletcher et al., 2007).

4.2 **PCI Membranes**

PCI Membranes is a subsidiary of the Xylem group of companies, a global acting water company offering a wide variety of water technology product brands. PCI Membranes, a company originally established in the late 1960s, offers MT UF products ranging from 6 to 12.5 mm in diameter which are available in PVDF polymers. Membranes based of other materials (such as PES, PS, PAN, CA and various thin film composites) are also offered for niche industrial separation applications. Xylem Inc. also offers immersed technology through its 2011 agreement with GE (Judd, 2014).

PCI was contacted in order to estimate membrane costs and those values were used as estimates during this study.

4.3 **Case study – Arla Dairy, Aylesbury, UK**

The 400-700 m^3/d milk processing processing effluent treatment plant at the Arla Dairy in Aylesbury in the UK is based on the Veolia Water Systems' *Memthane* anaerobic sMBR process. In this case anaerobic treatment was pre-selected by the client, whose stated ambition for the new dairy was for the installation to showcase sustainable development, applying advanced effluent treatment process technologies incorporating renewable energy.

The wastewater, at 14-27 ºC (22ºC average) and having a mean COD of 11,700 mg/L, is coarse-screened, chemically-conditioned, and equalized for 16 h (at the maximum flow) before passing through a heat exchanger and on to the bioreactor. The MLSS is held at a concentration of 15,000 to 30,000 and recirculated through a bank of 6 loops of 7 modules at a CFV of 1.5-3.5 m/s. At a TMP of 0.1-0.5 bar the flux generated is in the region of 12-20 LMH. The membranes are cleaned with monthly citric acid and hypochlorite CIPs (Judd, 2014).

The effluent is post-treated with flash aeration to remove residual COD, achieving more than 99,5% removal of the feed COD overall before being discharged in the local municipal sewage system.

5 Results

5.1 Sizing criteria

In the following table, the main sizing criteria and characteristics of the recommended anaerobic digester are summarized.

Table 5.1-1: Main sizing criteria and anaerobic digester characteristics.

PARAMETER	**UNIT**	**VALUE**
SIZING PARAMETERS		
Máximum Flow	**m^3/h**	3.5
Volumetric Organic Loading	**kg COD/(m^3.d)**	3.5
COD removal	**%**	> 90
Temperature	**°C**	52
REACTOR CHARACTERISTICS		
Nº of reactors	**-**	1
Volume	**m^3**	2000
DIGESTATE QUALITY		
COD	**mg/L**	5.000 – 10.000
TSS	**mg/L**	4.000 – 5.000
BIOGAS PRODUCTION		
Biogas Production	**Nm^3/d**	4.500
Methane Production	**Nm^3/d**	2.700
Biogas energetic potential	**kWh/d**	27.000
Cogenerator electric potential	**kW**	550
Electric energy production	**kWh/d**	11.475
	MWh/year	4.188
Thermic energy production	**kWh/d**	10.962
	MWh/year	4.001

As can be seen above, codigestion of the organic waste will lead to a high rate of biogas production. This gas can be used for the production of both heat and electricity for self-consumption, from a cogeneration unit, with significant economic benefits.

It's important to mention that a part of the thermic energy generated in the cogeneration process will be used in heating the anaerobic digester tank. Therefore, it is estimated that the thermic energy necessary to the digester heating will be one third of the total energy produced.

Table 5.1-2: Membrane filtration design parameters.

PARAMETER	UNIT	VALUE
Required Membrane Area		
Sustainable flux	**LMH**	7.5
Safety Factor	**-**	1.5
Area	**m^2**	313
Gas Sparging Requirements		
SADm	**$m^3/m^2/h$**	0.2
Gas Compressor required capacity	**m^3/h**	63

Presented in Table 5.1-2: Membrane filtration design parameters., an estimated total membrane area requirement of 313 m^2 is proposed.

Specific aeration demand was estimated at 0.2 $m^3/m^2/h$, which translates as a required capacity for the gas compressor as 63 m^3/h.

5.2 Cost-benefit analysis

In this chapter an investment cost estimate analysis is presented. The following components where considered when calculating the investment expenses:

- Construction costs, which include preparation of the terrain, the construction of the treatment facility components, operation and treatment buildings, exterior arrangements and hydraulic circuits;
- Costs related to acquiring and installing equipment for the energy recovery of organic waste;
- Costs of electrical installations, instrumentation, automation and monitoring.

Regarding the WWTP's operational costs, the following components were considered:

- Expenditures related to electromechanical equipment maintenance, including the cogeration unit;
- Expenditures with energy, which are related to the electrical equipment installed;
- Expenditures with acquiring chemical reagents used in the treatment process;
- Expenditures with staffing, which include the manual labor related to the facility's operation, from the operating director, electromechanical engineer, to the chemical analyst and the WWTP's operator.

In the following tables, an estimate of the investment and exploration costs is presented for the organic waste energy recovery of this pastry facility, in the conditions described above.

Table 5.2-1: Investment costs.

Investment Costs	**Value**
Anaerobic digester, including construction	1.2500.000 €
550 kW Cogeneration Unit, contained, including biogas treatment	500.000 €
Total Investment	**1.750.000 €**

Table 5.2-2: Operational costs.

Yearly Operational and Maintenance Costs	**Yearly Value**
Maintenance (equipment, electrical installations and construction)	36.000 €
Energy	10.000 €
Reagent costs	5.000 €
Manual labour	7.500 €
Analytical Control	1.000 €
Operation and maintenance total	**59.500 €**

Membrane costs

During the beginning stages of this project a pricing request was made to a largely known membrane manufacturer. Upon analysis of the pricing given, its possible to conclude that the price per m^2 of membrane area is approximately 4000 to 5000 €/m^2. That being said, the 313 m^2 membrane area requirements estimated for this current project would have a total cost of 1.250.000 to 1.550.000 €, approximately.

6 Conclusion

In this study, an anaerobic membrane bioreactor was proposed as a solution to the treatment of a pastry facility wastewater with the objective of producing a high-quality effluent. A degree of energy recovery was also achieved through the use of a cogeneration unit. Based on the results on the calculations made, the following conclusions can be drawn:

- The AnMBR can be an appropriate treatment method to a high strength wastewater such as the one from a pastry industry. COD removal efficiencies from 90 to 95% with an OLR of 3 kg/m^3/day.
- The reactor would work at a fairly stable MLVSS concentration of 6 to 15 g/L with a total reactor volume of 2100 m^3.
- Effluent COD concentration in the range of 500 to 1000 mg/L could be achieved.
- The daily methane production is 2700 Nm^3/day with an approximate energetic potential of 20.000 kWh/day.
- The membrane permeate flux would operate at approximately 7.5 LMH. Due to a relatively high permeate flux, twice a week cleaning is suggested. Cleaning can be achieved through scouring with biogas produced and periodic membrane maintenance cleaning which can help to keep stable membrane flux and restrict membrane fouling.
- The values and assumptions hereby presented should be used as a starting point and a baseline for further planning and eventually implementation as a real-life solution for this pastry facility.

7 Final Considerations

This study is theoretical and includes several estimates and safety factors, therefore the results may be overestimated but it’s safe to assume they’re reasonable and possibly accurate with reality. That being said, a follow up analysis of the practical implementation of the options solutions studied here, would be an interesting complement to this work, along with verification of the treatment efficiencies hereby represented.

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