Membrane Bioreactors in Wastewater Treatment: Future is Now

Adrià Ugidos Baqueró

adria.ugidos@gmail.com

Departament of Civil Engineering, Architecture and Georesources

Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

September 2018

ABSTRACT: Generating a sustainable water cycle based in reusing treated wastewater is essential in the long term to solve the stress of the available freshwater resources and avoid increasing the planet contamination. Many advanced treatments have been developed during the last decades to improve the effluent quality offered by the traditional processes in wastewater treatment plants (WWTP) in order to achieve the treated wastewater reuse minimums demanded by the current regulation. As a consequence, advanced treatment design has probably become the most challenging aspect in a WWTP.

Membrane bioreactors (MBR), an advanced treatment which combines the activated sludge process with the membrane filtration, are gaining more attention day by day. Able to substitute an entire line of secondary and tertiary treatments, these compact systems obtain excellent effluents ready to be reused in most of the cataloged uses, being especially interesting when space is a limiting factor and for upgradings thanks to their adaptability to conventional activated sludge processes. The market expansion of this technology during the last years induced a reduction in membrane capital costs and an energy demand optimization search, overcoming one of the MBR major classic drawbacks and becoming an attractive alternative in economical terms when high quality effluents are desired. Fundamental operational criteria are reviewed in order to achieve an optimal system performance, giving special attention to fouling maintenance, control and prevention strategies. Finally, a mathematical model has been developed to design a compact MBR plant based on all the information presented and discussed during this thesis.

Keywords: Membrane bioreactor, Membrane filtration, Activated sludge, Recycle, Wastewater treatment technologies, Wastewater treatment plant.

---

1. The Wastewater Importance

Traditionally water had been mistakenly considered as an unlimited resource. Our society has undergone a great development at all levels. As a consequence, water consumption is considered to be six times higher nowadays than at the beginning of the XX century and is expected to continue growing. Moreover, our social model achieved a big evolution as well with several impacts on global environment because of contamination.

During the last century wastewater began being recollected and treated in wastewater treatment plants (WWTP), where the influent was usually submitted at what is known as preliminary, primary and secondary treatments before being discharged into the media in order to stop expanding contamination in the water cycle. This conception has continued evolving as, despite contaminants are importantly reduced after those treatments, the effluent continues containing pollutants, recognizing the importance of reusing treated wastewater to generate a sustainable water cycle in the long term. Many tertiary or advanced treatments have appeared to achieve different effluent quality levels required by the current legislation, probably becoming the most challenging aspect when a WWTP is designed.

Membrane bioreactors (MBR) are an alternative advanced treatment which combines the activated sludge process and the membrane filtration to achieve excellent effluent qualities. These systems are gaining more attention day by day because of their maturity, what has provided them performance reliability as well with an increased market competence between manufacturers that has produced an attractive drop in membrane capital costs and an energy optimization search in terms of operational costs, two of their major classic drawbacks.

2. Wastewater Contaminants

It is necessary to know the physical, biological and chemical wastewater components before applying the right treatment. A list of principal physical characteristics, organic, inorganic and gaseous chemicals and biological constituents are presented and described to understand the wastewater characteristics, how they are measured and their usual concentrations.

A final emphasis is placed on contaminants of emerging concern (CEC), a group of substances which have adverse effects on human and wildlife endocrine systems that have been recognized as significant water pollutants in recent years.

3. Wastewater Treatment Objectives and Regulations

Treatment objectives have been evolving since the importance of treating wastewater was recognized, becoming more restrictive day by day. Actually, directive 2000/60/EC launched the European Union commission regulates the contaminant levels of the treated wastewater being discharged into the environment in European countries, focused on removing suspended solids, organic matter and additionally nitrogen and phosphorus, nutrients guilty of causing eutrophication in sensitive areas. Classic preliminary, primary and secondary treatments are enough to fulfill those requirements.

European Union does not have a reused wastewater legislative framework. So, Spanish regulation RD 1600/2007, one of the most restrictive legislations in this field, has been used as a guideline during this thesis. In addition to further restricting the permitted levels of suspended solids and in this case the turbidity of the effluent with respect to the discharge regulation, it also adds restrictions mainly in terms of pathogens as intestinal nematodes or *Escherichia Coli*, classifying any specific reuse in different categories with individual requirements grouped in 5 general groups. Tertiary or advanced treatments are needed after secondary treatment in WWTP to achieve those effluent qualities.

In the future treated wastewater legislations for discharge and reuse are expected to become more restrictive if we want to reach a sustainable water cycle in the long term, not only by raising allowed contaminant limits nowadays, but also by imposing removing new pollutants such as CEC.

4. Conventional Secondary treatment

WWTP have traditionally followed a typical schema: preliminary, primary and secondary treatments, which obtain effluents able for being discharged into the media.

The purpose of preliminary treatments is to ensure that the plant can process satisfactorily the incoming wastewater flow by removing big suspended solids, inorganic grit, grease or oils. After that, wastewater is pumped into the primary treatment, which consists in a sedimentation tank where the wastewater is detained and smaller suspended solids and also oils and grease are removed by a gravity process. Finally, secondary treatment, also known as conventional activated sludge process (CAS), is focused on eliminating the remaining organic matter thanks to a biological process made by microorganisms. Following the contact period between wastewater and activated sludge, the outflow is separated from the generated sludge in a secondary settlement tank. Excessive sludge needs to be treated, accounting for about 50-60% of wastewater treatment total cost.

At the end of the conventional secondary treatment, between 80-95% of BOD, 80-90% of TSS and 90-98% of fecal coliforms are removed. Although principal contaminants have been considerably reduced at this point and the effluent fulfills discharge requirements, water continues being contaminated by several pollutants, generally under the reuse quality levels. Many tertiary or advanced treatments appear after the secondary treatment in order to achieve better effluents able for being reused.

5. Conventional Advanced Treatments

Advanced treatments are additional processes needed to remove remaining specific contaminants in wastewater. Their design is probably the most challenging aspect in a WWTP. Knowing influent and desired effluent characteristics, limitations in capital (CAPEX) costs and operational (OPEX) costs, available physical space or compatibility with existing facilities if an expansion is being carried out are crucial aspects that must be examined in detail for finding an optimal solution.

Nitrogen and phosphorus, principal nutrients of concern in wastewater treatment, are usually removed thanks to biological processes. On the one hand, nitrification-denitrification is used for nitrogen elimination, process consisting in oxidizing ammonia to nitrite and then to nitrate made by specific bacteria, *Nitrosomonas* and *Nitrobacter*. Their growth is achieved by extending the aeration and the age of the sludge inside the biological tank from the conventional secondary treatment. Second step, denitrification, needs the absence of oxygen to transform nitrite into nitrate. To do so, the conventional secondary treatment suffers another transformation, installing an anoxic tank before the biological tank, configuration known as the modified Ludzack-Ettinger process (MLE). Bardenpho process is another usually selected configuration, consisting in two anoxic and biological stages, respectively. On the other hand, phosphorus is also usually removed thanks to biological processes. In this case, phosphate-accumulating organisms (PAO) are exposed to aerobic and anaerobic conditions. Therefore, nutrient removal systems, as A^2/O, modified Bardenpho or oxidation ditches are formed by anoxic, anaerobic and aerobic zones. Phosphorus can also be removed chemically by the addition of metal salts, generally ferric chloride or aluminum sulfate.

Despite suspended solids (SS) have been considerably removed at the end of a conventional secondary treatment, reusing wastewater requires less SS quantities. Coagulation-flocculation is a common treatment to achieve so by adding a coagulant, generally ferric chloride or aluminum sulfate, that allow colloidal particles the potential to stick together forming flocs, decanted by a final sedimentation process. A superior SS removal treatment, usually placed after the previous one, is the granular filtration using constructed beds of sand, trapping suspended materials between the grains of the filter media while the wastewater passes through the granular material.

Disinfection has become one of the primary treatments for the pathogens removal. Chlorine, ultraviolet radiation and ozone are the principal disinfectants used to treat wastewater. In general terms, bacteria are highly susceptible to all three options, helminth eggs and protozoan cysts are more resistant to chlorine and certain viruses to UV, being ozonation the most effective disinfection method, especially for viruses. Despite being the last cost-effective option, ozone also has the capacity of removing a large amount of CEC, identified as an interesting quality in the long term.

Three advanced treatment lines are proposed based on the information provided and discussed in order to achieve different effluent quality levels:

- Discharge to sensitive area: Nutrients removal is fulfilled by modifying the conventional activated sludge process by introducing anoxic and anaerobic zones.

- Reuse quality B: Granular filtration and disinfection are added after the conventional secondary treatment for obtaining concentrations below 10 mg/L of SS, 10 mg/L of BOD, 5 NTU of turbidity and between 200 to 10.000 CFU/100 mL of *E. Coli*. The effluent could be reused for 2.2, 2.3, 3.1 or 4.2 qualities stipulated by the Spanish reuse regulation.

- Reuse quality A: Coagulation-flocculation, granular filtration and disinfection are added after the conventional secondary treatment for obtaining concentrations below 10 mg/L of SS, 10 mg/L of BOD, 3 NTU of turbidity and 200 CFU/100 mL of *E. Coli*. The effluent could be reused for 1.2, 2.1 or 4.1 qualities stipulated by the Spanish reuse regulation. Although this treatment line offers excellent effluents, is not able to ensure the absence of pathogens. Extra advanced treatments as membrane filtration will be needed.

6. Membrane Bioreactor (MBR)

Able to substitute an entire line of secondary and tertiary treatments, MBR are a less conventional advanced wastewater treatment which combines the activated sludge process with membrane filtration, meaning an important space advantage compared with CAS. Total retention of activated sludge inside the bioreactor allows operating under high mixed liquor suspended solids (MLSS) concentrations and elevated solid retention times (SRT), generally between 9 to 15 g/L and 20 to 40 days, respectively. With lower hydraulic retention times (HRT), the bioreactor size is reduced, resulting in attractive compact systems with an excessive sludge minimization.

Membrane Filtration

Filtration by membranes offers an excellent effluent, practically allowing the complete retention of SS and pathogens. The process is done in MBR using microfiltration (MF) or ultrafilration (UF) membranes over the lower-sized reverse osmosis (RO) and nanofiltration (NF) membranes, more expensive and energy demanding. Despite being relatively bigger-sized membranes, the permeate effluent has practically the absence of SS and pathogens, being a barrier for reuse required contaminants. MBR membranes are usually made of polymeric materials such as cellulose polymers.

Membrane Modules

Membranes are mounted in modules or cassettes, including supporting frames, permeate flow connections and aeration ports at the bottom of the cassette for keeping the biomass in suspension and producing a turbulent two-phase flow velocity on the membrane surface to limit the fouling deposition. Membrane media is manufactured as flat sheets, hollow fibers or tubular fibers, then configured into hollow-fiber, spiral-wound, multi-tubular or flat-plate modules. MBR systems usually use hollow-fiber cassettes because of their compactness and economic advantage or plat-plate modules because of their low energy demand.

MBR configuration

Depending on the membrane location, MBR systems are configured externally or submerged.

External or sidestream were the first MBR generation, with the membranes located outside of the biological reactor. When the organic content of the wastewater is aerobically stabilized, mixed liquor is pumped to the external dry membrane modules at high cross-flow velocities. Filtered wastewater is extracted from the system while biomass is returned to the bioreactor. Despite external MBR have low aeration costs and allow high operational fluxes, all the process described before requires a lot of energy, increasing their operational costs. For this reason, this configuration has rarely been developed in large scale. Airlift MBR have recently been developed as an innovative and promising external MBR configuration, using air as the main force for the activated sludge circulation, reducing the energy consumption compared with conventional cross-flow external MBR.

Second generation and mostly used internal or submerged MBR introduced the membranes directly immersed inside the bioreactor. A relatively small negative pressure imposed on the permeate site acts as the driving force for the effluent to be permeated through the membranes, considerably reducing the energy demand. Unique tank configuration is more efficient for small treatment systems but it not adapts very well to larger or more nutrient removal demanding treatment systems, where separating the membranes in a second tank allows better performances, mainly thanks to the possibility of individualizing the specific requirements of the activated sludge and the filtration processes. This configuration is recommended nowadays because of its extended use, offering more reliability as there is much more information about its experimental performance. Therefore, further discussion about operational criteria and costs will be focused on submerged MBR.

MBR Operating Conditions

A MBR system design needs to consider the incoming wastewater characteristics. It is very important to receive well-treated wastewaters for the proper performance of the membrane filtration process. For this reason, MBR are usually situated after preliminary and primary stages in a WWTP. However, a fine screen size of around 0,5 mm is installed at the entrance of the bioreactor to remove materials that can tangle around the membrane fibers.

Flux, one of the fundamental MBR design parameters, is the velocity at which the wastewater passes through a spatial unit of membrane, indicating the system productivity. To achieve operational sustainability, conventional submerged MBR should have modest fluxes between 15 to 25 $L/m^2 \cdot h$, resulting in transmembrane pressures (TMP) of generally less than 50 kPa.

Main MBR operating conditions include SRT and HRT, indicating the average time the activated sludge solids are in the system and the average time the influent wastewater remains inside the system, respectively. One of the main advantages of the MBR systems is that they can decouple both parameters. Long SRT are applied, usually between 20 to 40 days, resulting in high MLSS concentrations between 9 to 15 g/L and low food to microorganisms ratios (F/M) between 0,05 and 0,15 day^{-1}. As a consequence, much less wasted sludge is produced with respect to CAS, importantly the related treatment operational costs. On the other hand, operating with short HRT, usually between 2 to 8 hours, is desirable to increase the permeate quality and reduce the space needed for the system.

It is possible to achieve nutrient removal in MBR. In terms of nitrogen, operating with long SRT allow nitrifying bacteria not being recirculated out of the bioreactor, achieving the nitrification process. Denitrification can be done by using intermittent aeration alternating aerobic and anoxic time phases, optimizing space needed with respect to pre-denitrification and post-denitrification, the other two ways to achieve denitrification by the addition of an anoxic tank before or after the biological tank, respectively. On the other hand, several experiences have shown difficulties to achieve high phosphorus removals (usually between 50 to 70%) in MBR operating with long SRT. Adding aluminum sulfate during the activated sludge process is necessary to achieve removal levels over 90%. Another possibility to highly remove phosphorus is installing an anaerobic tank in the MBR system.

Membranes air scouring and the activated sludge aeration are the major components of the MBR energy consumption (60-80%). The size of the bubbles has a great impact on the system performance: activated sludge operates better with small bubbles, while big bubbles are optimal for the membrane filtration. The introduction of intermittent aeration represented a big improvement in terms of energy consumption. Specifically, limiting aeration for 10 seconds every 40 seconds ("10:30") has been found better than every 20 ("10:10") or 70 seconds ("10:60") without significant impacts on fouling rates compared with continuous aeration, with energy demand savings up to 75%.

Solids agglomeration at the entrance of the membrane channels is known as clogging. The major measure to prevent this phenomenon consists in installing a fine screen at the entrance of the MBR system. The air distribution is an important concern, being important to install some of the air diffusers at the bottom of the membrane cassettes for an adequate air scouring. Limiting MLSS concentration is another way to control clogging, especially in hollow-fiber MBR.

Fouling

Material deposition onto membrane surface is known as fouling, considered the main operational problem in MBR, implying a flux reduction operating at constant TMP and therefore affecting the system productivity. It is important to find an optimal combination between fouling maintenance, control and prevention strategies to achieve high net flux rates in the long term by minimizing the energy consumption, promoting the system productivity without damaging the membranes. Fouling prevention begins with a proper influent pre-treatment.

Many membrane characteristics have been found directly related with fouling. Membranes with hydrophilic surfaces are less susceptible to this phenomenon. Commercial membranes are usually made of hydrophilic polymers. Different techniques are available to increase the membranes hydrophilicity by modifying their surface. Charging the membranes surface with the same electrical charge of the foulants or pattering their surface as pyramids or prisms are also relevant aspects. Packaging membrane modules with lower densities and using membranes which allow transversal, longitudinal or rotational movements, produces less fouling.

Numerous maintenance strategies are used to control fouling in MBR. Backwashing is a physical process used to remove contaminants accumulated on the membranes by reversing the flow direction using a fixed cycle time or operating with a maximum TMP value, usually combined with chemical cleanings. Key backwashing parameters are duration, frequency and backwash flux. Permeate loss and membrane damages or effluent contaminations shown by different backwashing experiences make relaxation becoming more attractive, intermittently suspending permeation by time cycles (commonly intervals of 1 minute every 10 minutes) and therefore being less aggressive for the membranes without losing permeate in the process.

Physical processes need to be combined with periodic chemical cleanings to eliminate residual or irreversible fouling. It is important to smartly apply chemicals, as prolonged exposures cause oxidative damage to membranes, tending to be a combination between maintenance cleanings at moderate chemical concentrations of 200 -500 mg/L of NaCOl every 2 - 4 weeks in cycles of 30 - 120 minutes in situ for the residual fouling, and intensive cleanings at high chemical concentrations of 0,2 - 0,3 weight percentage (wt%) of NaCOl coupled with 0,2 – 0,3 wt% of citric acid once or twice a year, draining the membrane tank to remove irreversible fouling.

Mixed liquor chemical modification is an interesting tool to reduce fouling. It could be achieved by adding coagulants as ferric chloride or aluminum sulfate and absorbents as powdered activated carbon (PAC) or granular activated carbon (GAC), absorbing and degrading the biofilm layer on the membranes surface. Using any of these products or combinations between coagulants and absorbents open the door of being continuously operating.

Some experiences showed a fouling reduction using techniques to inhibit quorum sensing (QS), language used by bacteria to communicate and asses their population density, becoming a promising alternative for fouling control. However, they need to continue being studied to see their efficiency in large scale MBR. Applying electrical fields or ozone are other techniques for fouling control which could gain more attention in the future.

Feedback control systems are seen as an interesting tool to achieve an adjustable control of fouling maintenance, control and prevention strategies during the system lifetime.

MBR Performance

Parameter	Concentration
BOD [mg/L]	< 5
SS [mg/L]	< 1
Turbidity [NTU]	< 0,2
Total Nitrogen [mg/L]	< 5
Total Phosphorus [mg/L]	< 0,5
Intestinal Nematodes [egg/10 L]	< 1
Fecal Coliforms [CFU/100 mL]	< 50

Table 1. Conservative standard MBR effluent quality.

The conservative standard MBR effluent quality presented in table 1 has been contrasted by several experiences, including the study of four commercial MBR systems analyzed during this thesis, showing that these systems can effectively substitute an entire line of CAS with coagulation-flocculation, granular filtration and disinfection treatments, obtaining even better results in terms of contaminants removal.

Absence of fecal coliforms is the limiting factor to reuse the effluent in all possible regulated uses. Despite many experiences have shown MBR obtaining effluents with less than 10 CFU/100 mL and even the absence of *E. Coli*, a final disinfection method is recommended as a second pathogen barrier to ensure their absence.

In terms of CEC, MBR achieve better removal percentages than CAS in general terms. Adding GAC has significant benefits not only in terms of fouling, but also on CEC elimination, seen as a promising solution to provide high CEC removals in MBR. Ozone is highly recommended if a pathogen second barrier is desired because of its high disinfection and CEC removal capacities.

A MBR small-sized plant (with a maximum capacity of 1.000 m^3/d) used by three different textile industries for reusing wastewater produced by their industrial processes was visited during the development of this thesis.

MBR CAPEX and OPEX Costs

Traditionally, both excessive MBR CAPEX and OPEX costs had been the main reason of choosing other alternatives over them. However, development carried out to obtain more productive and less expensive membranes resulted in a market expansion of this technology, creating more competence between manufacturers that induced a reduction in membranes capital costs and an energy demand optimization search during the last decades.

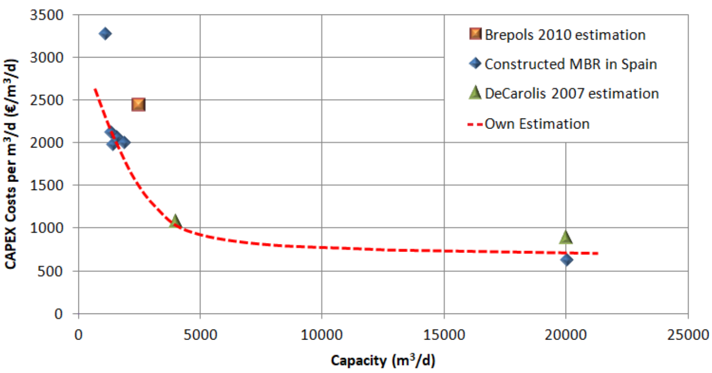

Figure 1. MBR CAPEX costs trend curve.

Prices of different constructed MBR plants in Spain and estimations done by different studies have been taken into account to elaborate a MBR plant CAPEX costs trend curve depending on its size, seen in figure 1.

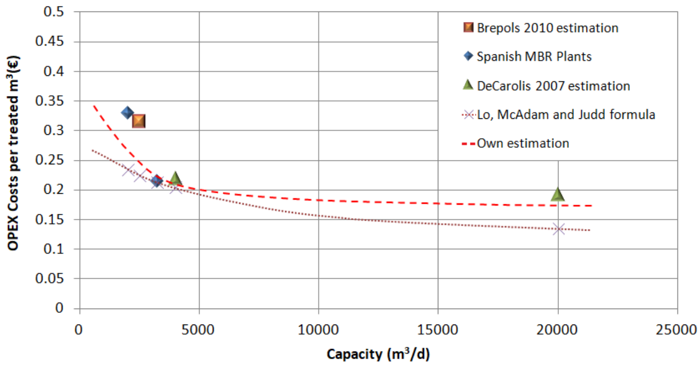

Figure 2. MBR OPEX costs trend curve.

Same process has been done in terms of OPEX costs, obtaining the red OPEX costs trend curve seen in figure 2.

MBR CAPEX and OPEX cost estimations have been compared with CAS with and without tertiary treatments. On the one hand, is more cost-effective a CAS than a MBR plant. Therefore, if a new WWTP is projected for discharging the effluent into the environment, CAS is recommended over MBR in economical terms. On the contrary, if reusing the effluent is desired, constructing a MBR plant would be more cost-effective than constructing a CAS plant with coagulation-flocculation, granular filtration and a disinfection treatment, especially in terms of CAPEX costs, usually representing an important limitation for the municipality owner of the future WWTP. MBR systems are also recommended for upgrading cases from CAS plants not only because of their compactness and adaptability, but also because of their lower CAPEX and OPEX costs compared with an entire line of advanced treatments.

MBR Design

A mathematical model has been developed on Excel to design a compact MBR system based on all the information presented and discussed during this thesis. Despite its relative simplicity, the model has a high flexibility, allowing the user getting adapted to his particular case by introducing different inputs to provide all the basic outputs necessary to design a real MBR plant. The effects of the temperature have been seen transcendental, importantly affecting the biological growth. It has been found that the SRT is not directly related with the biological growth process and therefore it can be decoupled from the HRT. It would be interesting to investigate and calculate the pH effects of the influent wastewater in the MBR system performance.

7. Conclusions

MBR system are a mature alternative to conventional treatments that can substitute an entire line of secondary and tertiary treatments in a WWTP, achieving excellent effluents ready for being reused in most of possible regulated uses. Depending on the system performance, is recommended to add a pathogen second barrier if their absence is desired. Ozone is seen interesting because of its high disinfection and CEC removal capacities. The addition of GAC is also seen as a promising method to achieve high CEC removals.

Working with high MLSS concentrations and SRT results in a much lower wasting sludge generation (represents an important operational cost) and allow designing compact systems, being an attractive solution for new constructions where space is a limiting factor. MBR are especially interesting for CAS upgrading cases because of their low space demand and adaptability to CAS.

Submerged MBR are nowadays recommended over external MBR. Operational criteria, costs and design have been discussed in terms of submerged MBR.

It is important to find an optimal combination between fouling maintenance, control and prevention strategies. Relaxation is recommended over backwashing as a physical measure combined with periodical chemical cleanings. QS is seen as a promising alternative in the long term. Feedback control systems are seen as an interesting tool to achieve an adjustable control of fouling maintenance, control and prevention strategies during the system lifetime.

Constructing a CAS plant is more cost-effective than a MBR plant, recommended when achieving a discharge effluent quality is desired. On the contrary, constructing a MBR plant is more cost-effective than a CAS with coagulation-flocculation, granular filtration and a disinfection treatment plant, especially in terms of capital costs, which usually represent an important limitation for the municipality owner of the future WWTP.

Despite its relative simplicity, the mathematical model developed allows the user getting adapted to his particular case thanks to its high flexibility, obtaining all the basic information needed for designing a real MBR plant. Temperature effects have been seen transcendental for the biological process. SRT is not directly related with the biological process and therefore it can be decoupled from HRT.

References

Tchobanoglous, G., Burton F.L. *Wastewater Engineering. Treatment, Disposal and Reuse.* Metcalf & Eddy Inc. McGraw-Hill, 1995.

Gobierno de España. *Guía para la Aplicación del R.D. 1620/2007 por el que se establece el Régimen Jurídico de la Reutilización de las Aguas Depuradas.* 2010. <http://www.mapama.gob.es/es/agua/temas/concesiones-yautorizaciones/ GUIA%20RD%201620_2007__tcm30-213764.pdf>.

Official Journal of the European Communities. *Council Directive of 21 May 1991 concerning urban waste water treatment.* May 1991. <http://eur-lex.europa.eu/legalcontent/ EN/TXT/PDF/?uri=CELEX:31991L0271&from=EN>.

Arroyo. *Contaminants of Emerging Concern in Water.* 2013 <https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/Arroyo2013LR_0.pdf>.

Ireland Environmental Protection Agency. *Wastewater Treatment Manuals. Primary, Secondary and Tertiary Treatment*. 1997. <https://www.epa.ie/pubs/advice/water/wastewater/EPA_water_treatment_manual_preliminary.pdf>.

United States Environmental Protection Agency. *Biological Nutrient Removal Processes and Costs*. 2007. <https://www.epa.gov/sites/production/files/documents/criteria_nutrient_bioremoval.pdf>.

Beless B., Ardner J. *Drinking Water Treatment: Coagulation, Flocculation, and Sedimentation*. <http://gk12.egr.uh.edu/sites/gk12.egr.uh.edu/files/docs/lessons/Coagulation-Flocculation-Sedimentation.pdf>.

EPA Victoria. "Guidelines for Environmental Management". *Disinfection of Treated Wastewater*. 2002. <http://www.epa.vic.gov.au/~/media/Publications/730.pdf>.

United States Environmental Protection Agency. *Membrane Filtration Guidance Manual.* 2005. <https://www.sswm.info/sites/default/files/reference_attachments/EPA%202005%20Membrane%20Filtration%20Guidance%20Manual.pdf>.

Le-Clech, P. "Applied Microbiology and Biotechnology". *Membrane bioreactors and their uses in wastewater treatments.* Vol. 88 nº6 2010: 1253-1260

United States Environmental Protection Agency. "Wastewater Management Fact Sheet". *Membrane Bioreactors.* 2007. <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100IL7G.PDF?Dockey=P100IL7G.PDF>.

Kojic, P.S., Popovic, S.S., Tokic, M.S., Sijacki, I.M., Lukic, N.Lj., Jovicevic, D.Z., Petrovic, D.Lj. "Brazilian Journal of Chemical Engineering". *Hydrodynamics of an external-loop airlift reactor with inserted membrane.* Vol. 34 nº2 2017: 493-505

Jadhao, R., Dawande S. "International Journal of Chemical and Physical Sciences". *Effect of Hydraulic Retention Time and Sludge Retention Time on Membrane Bioreactor: Performance in Summer Season.* Vol. 2 nº2 2013.

Barillon, B., Martin, S., Langlais, C., Lazarova, V. "Water Science and Technology". *Energy efficiency in membrane bioreactors.* Vol. 67 nº12 2013: 2685-2691

Kraume, M., Bracklow, U., Vocks, M., Drews, A. "Water Science and Technology". *Nutrients removal in MBRs for municipal wastewater treatment.* Vol. 51 nº6-7 2005: 391-402

Gkotsis, P., Dimitra, B., Peleka, E., Zouboulis, A., Samaras, P. "Processes". *Fouling Issues in Membrane Bioreactors (MBRs) for Wastewater Treatment: Major Mechanisms, Prevention and Control Strategies.* Vol. 2 nº4 2014: 795-866

Ebrahim, A., Farhad, Z., Han, K., Leslie, G., William, K. "Applied Sciences". *The Performance and Fouling Control of Submerged Hollow Fiber (HF) Systems: A Review.* Vol. 7 nº8 2017: 765-805

DeCarolis, J., Adham, S. "Water Environment Research". *Performance Investigation of Membrane Bioreactor Systems During Municipal Wastewater Reclamation.* Vol. 79 nº13 2007: 2536-2550

Cazes, M., Abejón, R., Belleville, M., Sanchez-Marcano, J. "Membranes". *Membrane Bioprocesses for Pharmaceutical Micropollutant Removal from Waters.* Vol. 4 nº4 2014: 692-729

Lo, C., McAdam, E., Judd, S. "Water Science and Technology". *The cost of a small membrane bioreactor.* Vol. 72 nº10 2015: 1739-1746

DeCarolis, J., Adham, S., Pearce, W., Hirani, Z., Lacy, S., Stephenson, R. "Water Environmental Federation". *Cost trends for MBR systems for municipal wastewater treatment.* 2007: 3407-3418

Brepols, C., Schäfer, H., Engelhardt, N. "Water Science and Technology". *Considerations on the design and financial feasibility of full-scale membrane bioreactors for municipal applications.* Vol. 61 nº10 2010: 2461-2468

Iglesias, R., Simón, P., Moragas, L., Arce, A., Rodriguez-Roda, I. "Water Science and Technology". *Cost comparison of full-scale water reclamation technologies with an emphasis on membrane bioreactors.* Vol. 75 nº11 2017: 2562-2570