Aim of this book

Book hypothesis

The hypothesis of this book is that biofouling and organic fouling can be severely mitigated by understanding which key factors affect their development.

Key hypothesis

Chapter 1 – Reverse osmosis fundamentals

Reverse osmosis is the most effective technology to desalinate water.

Data normalization is a key tool to understand if a reverse osmosis membrane system operates as intended or if it is suffering from fouling.

Chapter 2 – Biofouling fundamentals

Biofouling is characterized by an initial phase of a flat pressure drop increase over time, followed by a second phase consisting of exponential growth.

Organic fouling is characterized by a sudden loss in normalized permeate flow that later tends to stabilize and plateau. This phase is typically characterized by a flat pressure drop if no biofouling occurs at the same time.

Chapter 3 – Membrane fouling simulators: a quick tool to study biofouling and why biofouling does not depend on flux

The membrane fouling simulator can be used to study biofouling with a small investment.

Membrane fouling simulators are able to mimic biofouling happening in real installations.

Biofouling does not depend on water flux.

Chapter 4 – The importance of the feed spacer to prevent biofouling

Feed spacers play a key role in preventing biofouling.

Without a feed spacer, biofouling hardly grows.

Fouling-resistant membrane chemistries can mitigate biofouling.

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Chapter 5 – The effect of the temperature and development of quick biofouling test

There is a temperature threshold that is needed for biofouling to start growing effectively.

Biofouling development depends on the availability of bioassimilable nutrients.

Biofouling can be accelerated by dosing bioassimilable nutrients.

Chapter 6 – Differentiating between biofouling and organic fouling during operation

The first fouling period is typically an organic fouling period.

The second fouling period is typically a biological fouling period.

Fouling is typically a combination of multiple fouling types.

Chapter 7 – Differentiating between biofouling and organic fouling on a membrane surface

A biofilm is mainly composed of EPS.

Biofouling can be distinguished from organic fouling by examining the portion of EPS in the entire fouling.

Biofouling development depends on the availability of bioassimilable nutrients.

Chapter 8 – Biofouling starts to develop before pressure drop starts to increase

TOC is quickly deposited on the membrane surface, leading to organic fouling.

ATP starts to accumulate after TOC has already accumulated.

ATP starts to accumulate on the membrane surface before the pressure drop begins to increase, ultimately leading to biofouling.

ATP on a membrane surface might be used as an early indicator to predict biofouling before it starts to develop.

Chapter 9 – Biofouling mainly happens in the lead elements

Biofouling mainly occurs in the lead elements.

It is very difficult to clean to the initial pressure drop once biofouling develops.

It is very difficult to fully remove a biofilm inside a reverse osmosis membrane.

Biocide cleaning can reduce the number of bacteria in a biofilm but does not help in preventing biofouling.

Biofouling can be easily brushed off or detached from the membrane and the feed spacer.

Organic fouling develops before biofouling starts.

Smart arrangement of feed spacers in a pressure vessel can reduce biofouling.

Chapter 10 – Biocides do not fully prevent biofouling

Dosing biocide allows the study of the initial organic fouling phase without biofouling interference.

Using biocides does not fully prevent biofouling.

Shock-dosing biocide does not fully prevent biofouling.

Fouling-resistant membrane chemistries can mitigate biofouling.

Chapter 11 – Visualizing biofouling on the membrane surface

Biofouling can be easily visualized and quantified on a membrane.

Biofouling mainly grows on the front elements in a pressure vessel.

Chapter 12 – Why preventing biofouling matters

A fouling-resistant element can reduce the number of chemical cleanings per year.

A fouling-resistant element can extend the operating time with the same number of cleanings.

Chapter 13 – Limiting nutrients to prevent biofouling in brackish water

Biofouling in brackish water can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

The same biofouling prevention technology can reduce total suspended solids.

This biofouling prevention system uses biomass, not a biofilm, to prevent biofouling.

Chapter 14 – Limiting nutrients to prevent biofouling in wastewater

Biofouling in wastewater can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

The same biofouling prevention technology can reduce cartridge filter replacements.
The same biofouling prevention technology can reduce organic compounds.

Chapter 15 – Limiting nutrients to prevent biofouling in seawater: part 1

Biofouling in seawater can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

The same biofouling prevention technology can reduce cartridge filter replacements.

Chapter 16 – Limiting nutrients to prevent biofouling in seawater: part 2

Biofouling in seawater can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

Key conclusions with key figures

Chapter 1 – Reverse osmosis fundamentals

Reverse osmosis is the most effective technology to desalinate water.

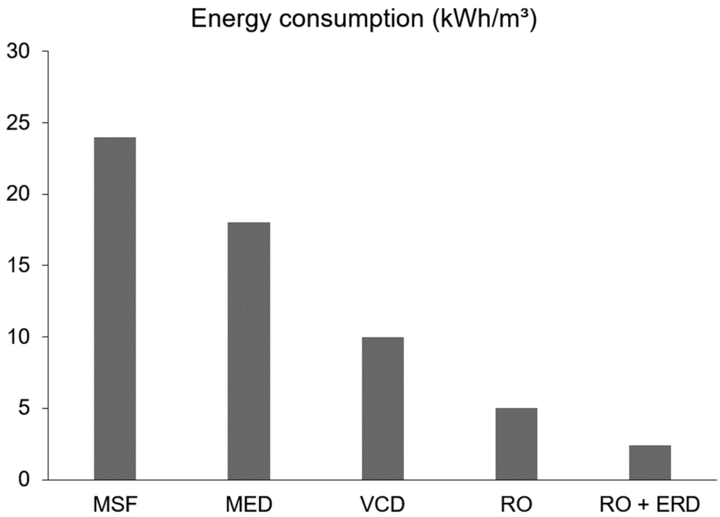

Figure 1: Energy consumption of different desalination technologies.

Data normalization is a key tool to understand if a reverse osmosis membrane system operates as intended or if it is suffering from fouling.

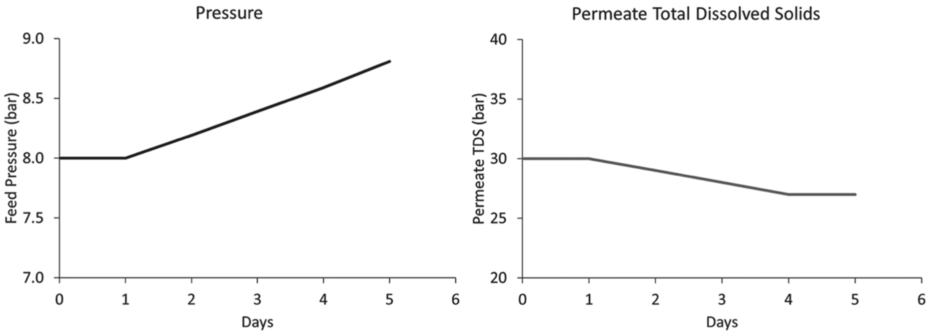

Figure 2: Feed pressure and permeate total dissolved solids' evolution.

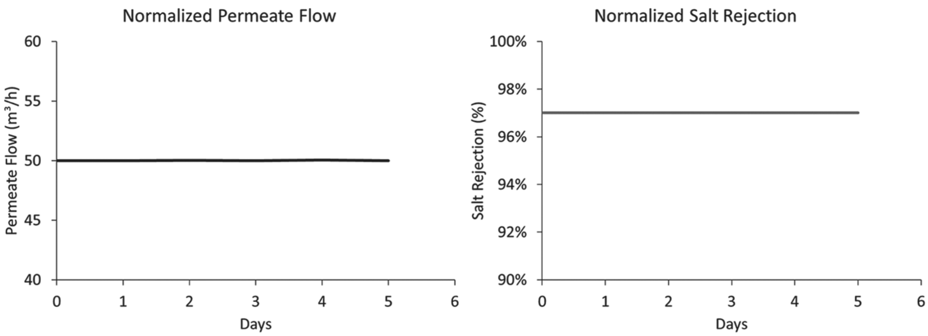

Figure 3: Normalized permeate flow and normalized salt rejection evolution.

Chapter 2 – Biofouling fundamentals

Biofouling is characterized by an initial phase of a flat pressure drop increase over time, followed by a second phase consisting of exponential growth.

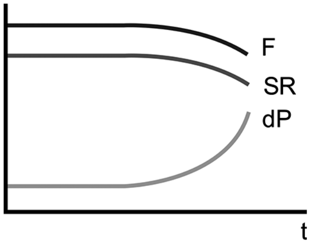

Figure 4: Biofouling typical behavior.

Organic fouling is characterized by a sudden loss in normalized permeate flow that later tends to stabilize and plateau. This phase is typically characterized by a flat pressure drop if no biofouling occurs at the same time.

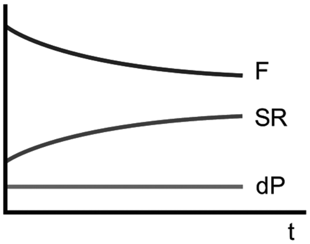

Figure 5: Organic fouling typical behavior.

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Membrane fouling simulators are able to mimic biofouling happening in real installations.

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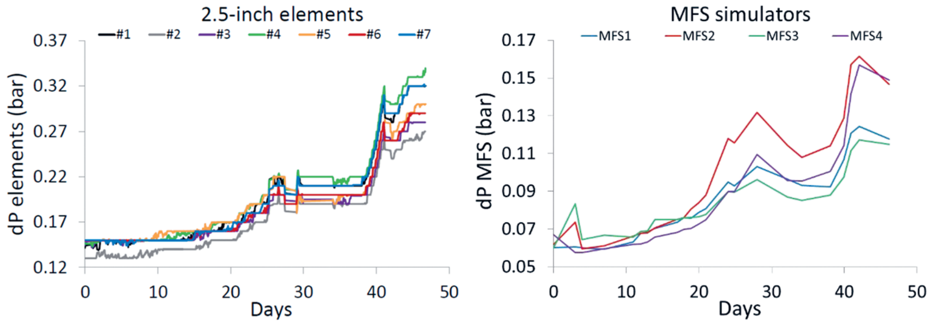


Figure 6: Pressure drop of MFS and 2.5-inch elements.

Chapter 4 – The importance of the feed spacer to prevent biofouling

The feed spacer plays a key role in preventing biofouling.

Without a feed spacer, biofouling hardly grows.

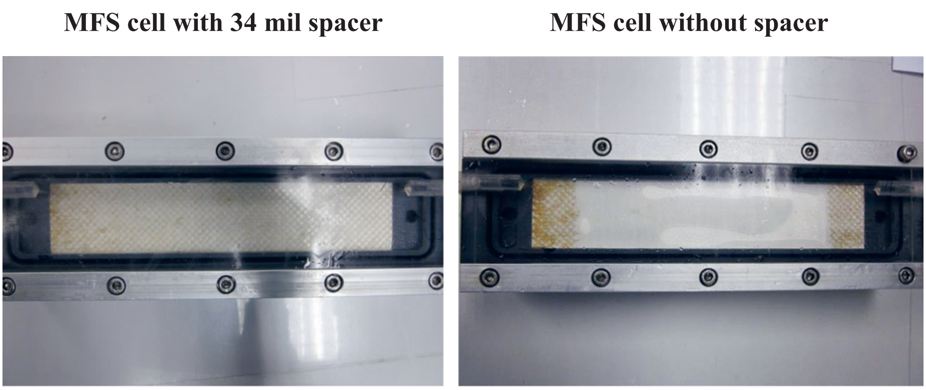


Figure 7: Biofilm distribution with and without a 34 mil spacer in the MFS cells.

Fouling-resistant membrane chemistries can mitigate biofouling.

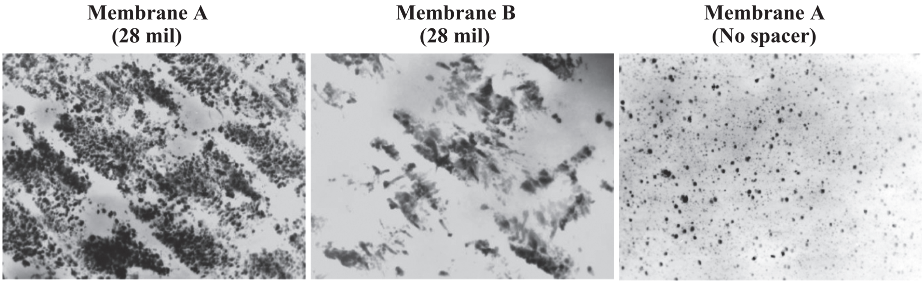


Figure 8: Biofouling developed on the membrane surface of Flat Cells.

Chapter 5 – The effect of the temperature and development of quick biofouling test

There is a temperature threshold that is needed for biofouling to start growing effectively.

Biofouling development depends on the availability of bioassimilable nutrients.

Biofouling can be accelerated by dosing bioassimilable nutrients.

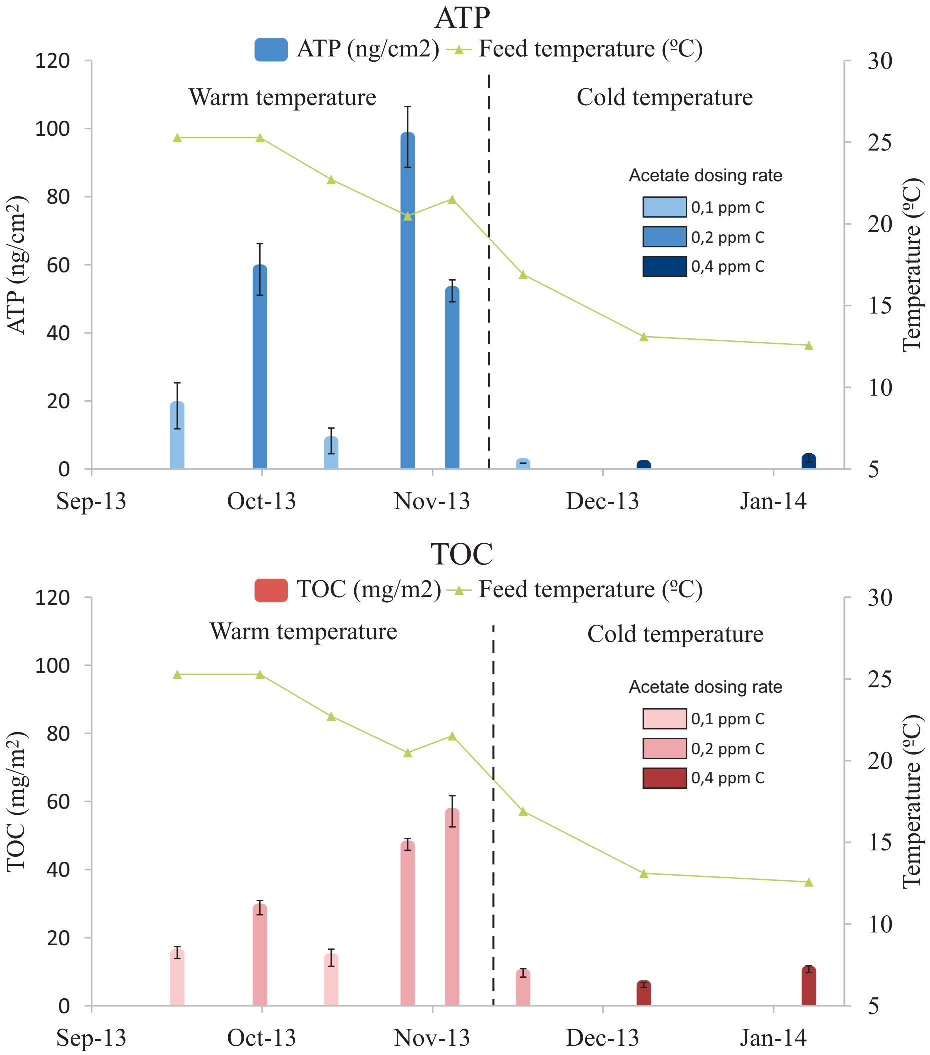


Figure 9: ATP and TOC evolution considering seasonal effect.

Chapter 6 – Differentiating between biofouling and organic fouling during operation

The first fouling period is typically an organic fouling period.

The second fouling period is typically a biological fouling period.

Fouling is typically a combination of multiple fouling types.

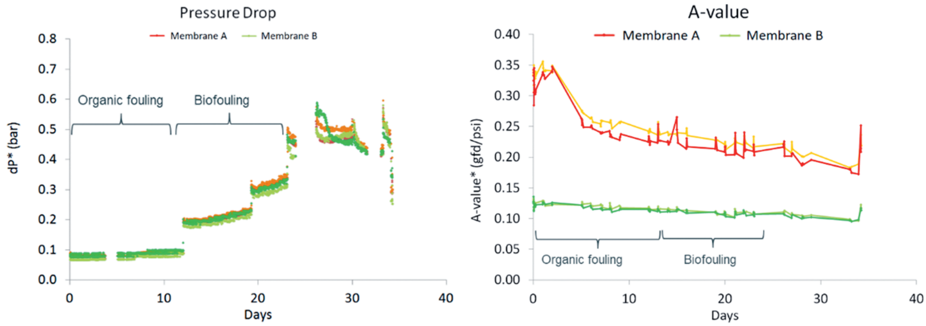


Figure 10: Pressure drop and permeability for Membrane A and Membrane B.

Chapter 7 – Differentiating between biofouling and organic fouling on a membrane surface

A biofilm is mainly composed of EPS.

Biofouling can be distinguished from organic fouling by examining the portion of EPS in the entire fouling.

Biofouling development depends on the availability of bioassimilable nutrients.

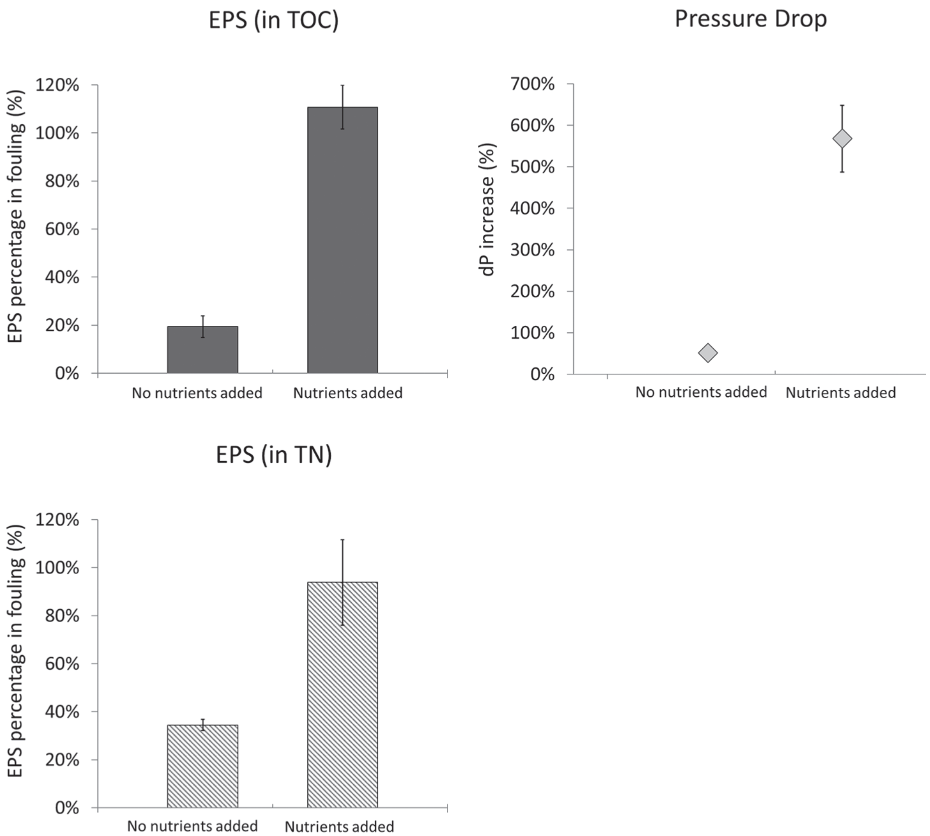


Figure 11: Correlation of membrane performance and EPS fraction for the two testing conditions.

Chapter 8 – Biofouling starts to develop before pressure drop starts to increase

TOC is quickly deposited on the membrane surface, leading to organic fouling.

ATP starts to accumulate after TOC has already accumulated.

ATP starts to accumulate on the membrane surface before the pressure drop begins to increase, ultimately leading to biofouling.

ATP on a membrane surface might be used as an early indicator to predict biofouling before it starts to develop.

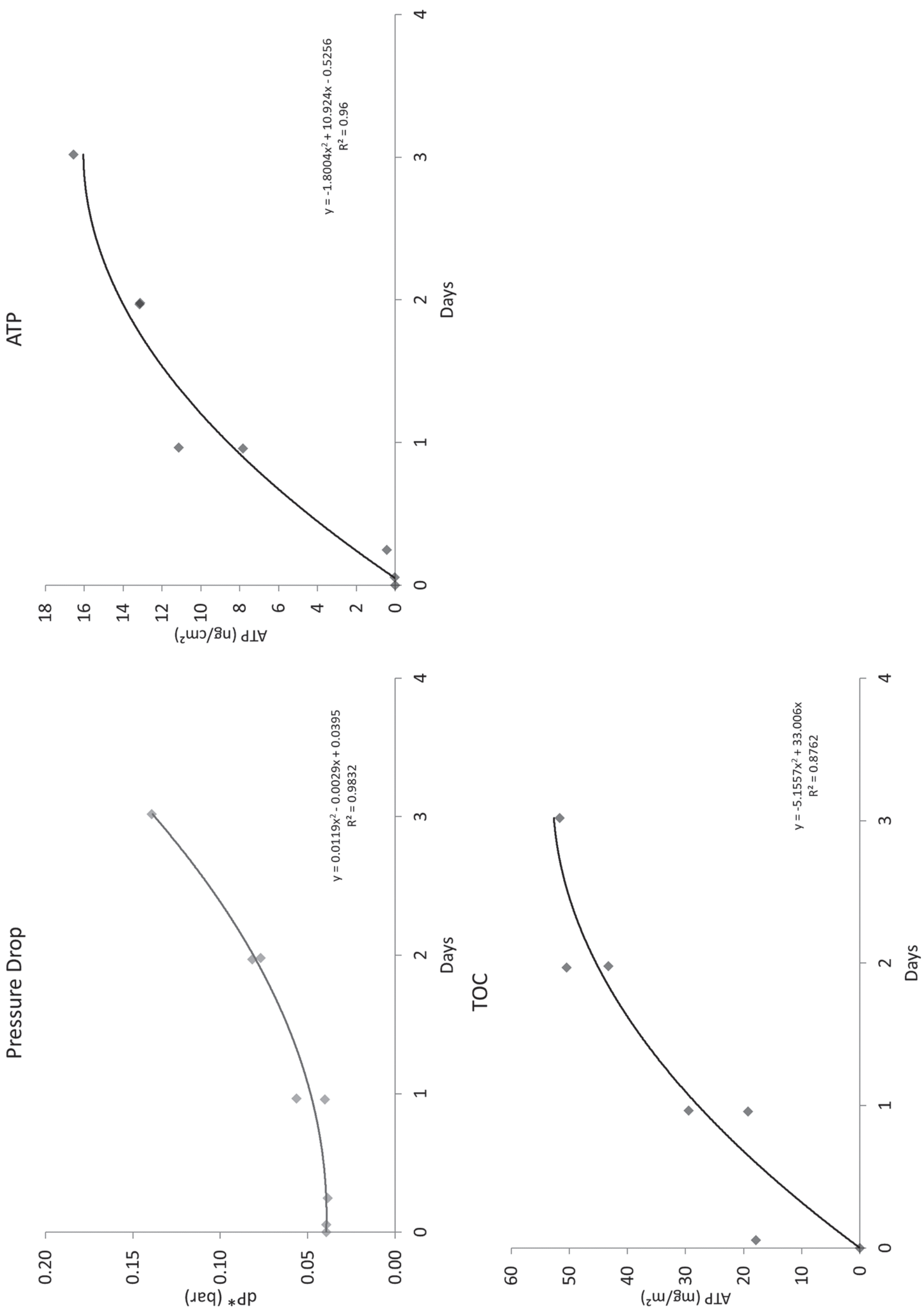


Figure 12: Pressure drop, ATC, and TOC of each membrane analyzed.

Chapter 9 – Biofouling mainly happens in the lead elements

It is very difficult to clean to the initial pressure drop once biofouling develops.
It is very difficult to fully remove a biofilm inside a reverse osmosis membrane.
Smart arrangement of feed spacers in a pressure vessel can reduce biofouling.

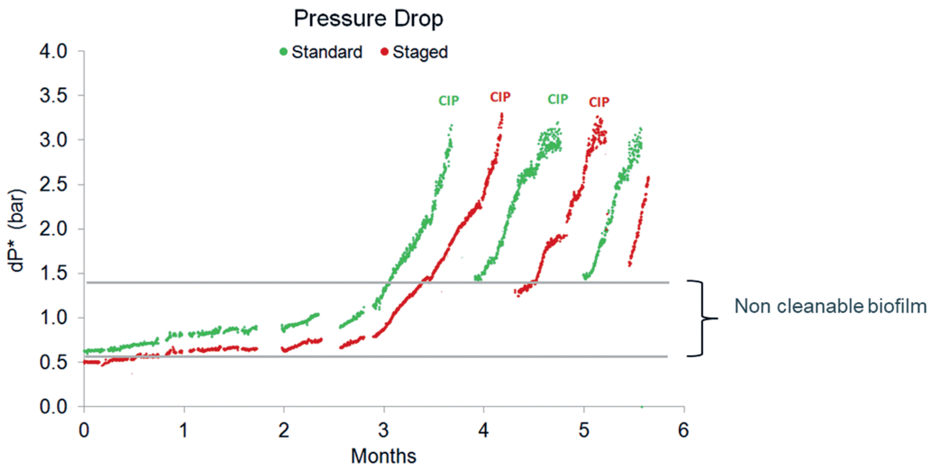


Figure 13: Pressure drop evolution.

Organic fouling develops before biofouling starts.

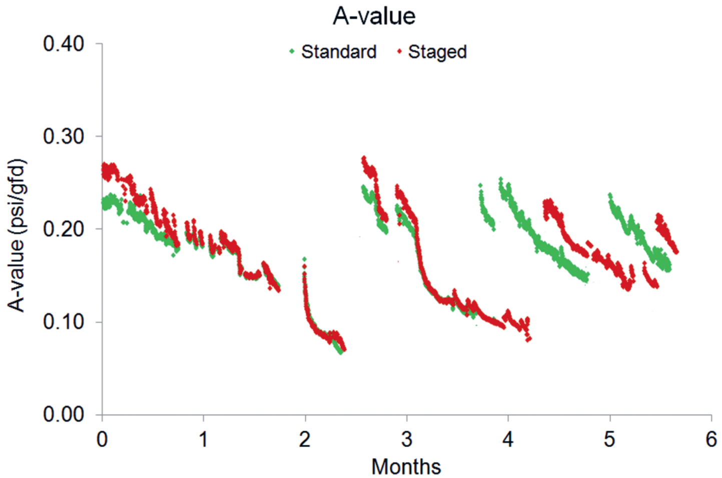


Figure 14: Water permeability (A-value) evolution.

Biofouling mainly occurs in the lead elements.

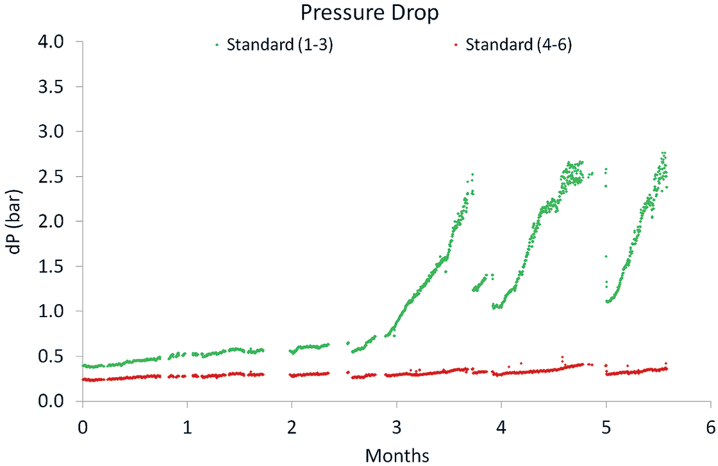


Figure 15: Pressure drop evolution in the tail and lead elements.

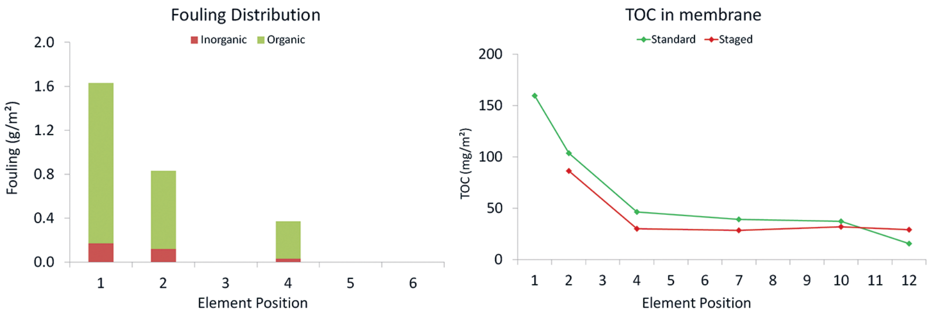


Figure 16: Fouling distribution across the pressure vessel.

Biocide cleaning can reduce the number of bacteria in a biofilm but does not help in preventing biofouling.

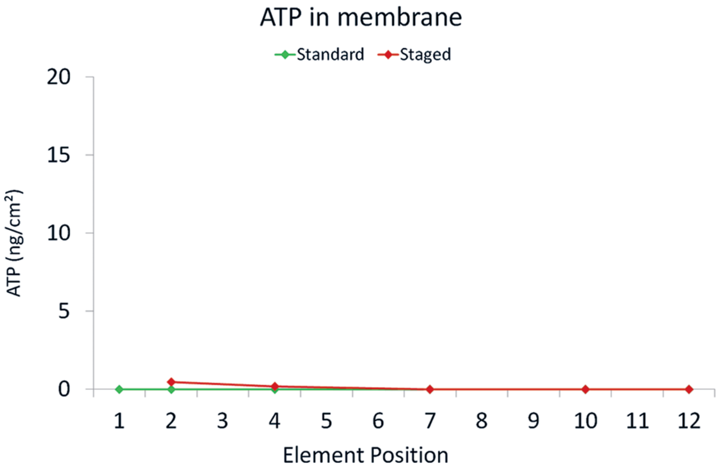


Figure 17: ATP distribution.

Biofouling can be easily brushed or detached from the membrane and the feed spacer.

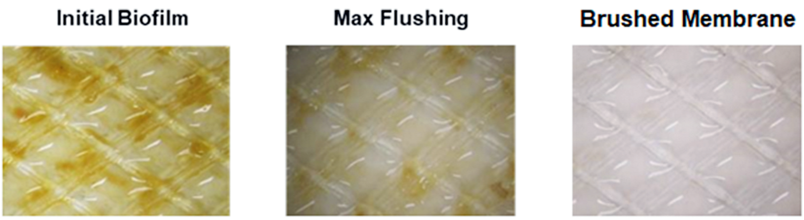


Figure 18: Membrane and feed spacer before and after the max flushing test, and after being manually brushed.

Figure 19: Scraping the biofilm.

Chapter 10 – Biocides do not fully prevent biofouling

Dosing biocide allows the study of the initial organic fouling phase without biofouling interference.

Using biocides does not fully prevent biofouling.

Shock-dosing biocide does not fully prevent biofouling.

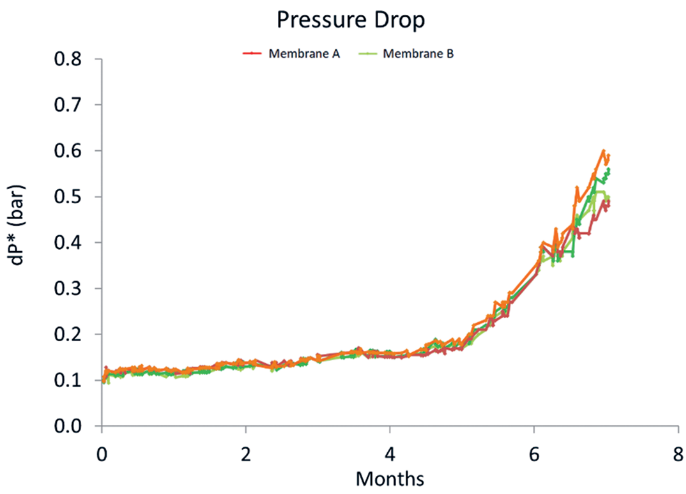


Figure 20: Normalized pressure drop evolution for Membrane A and Membrane B elements.

Fouling-resistant membrane chemistries can mitigate biofouling.

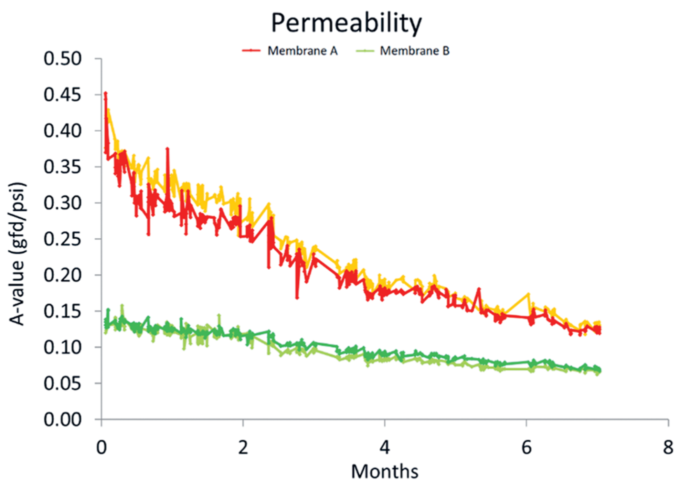


Figure 21: Normalized A-value evolution for Membrane A and Membrane B elements.

Chapter 11 – Visualizing biofouling on the membrane surface

Biofouling can be easily visualized and quantified on a membrane.

Biofouling mainly grows on the front elements in a pressure vessel.

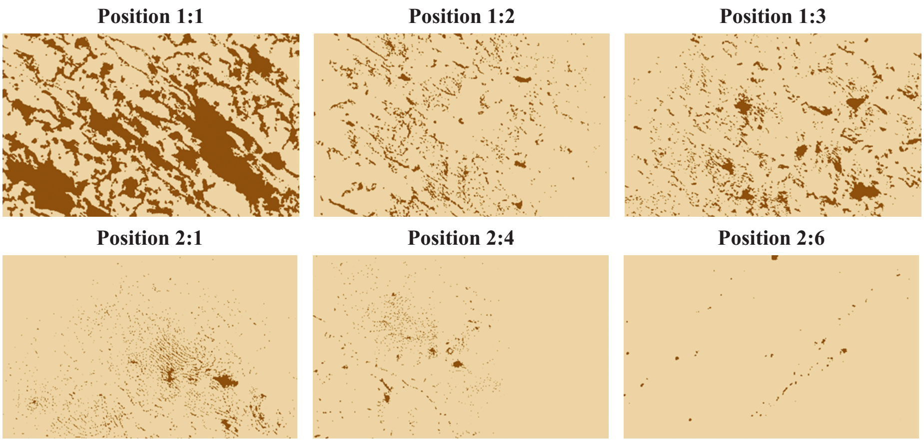


Figure 22: Biofouling distribution in a two-stage system.

Chapter 12 – Why preventing biofouling matters

A fouling-resistant element can reduce the number of chemical cleanings per year.

A fouling-resistant element can extend the operating time with the same number of cleanings.

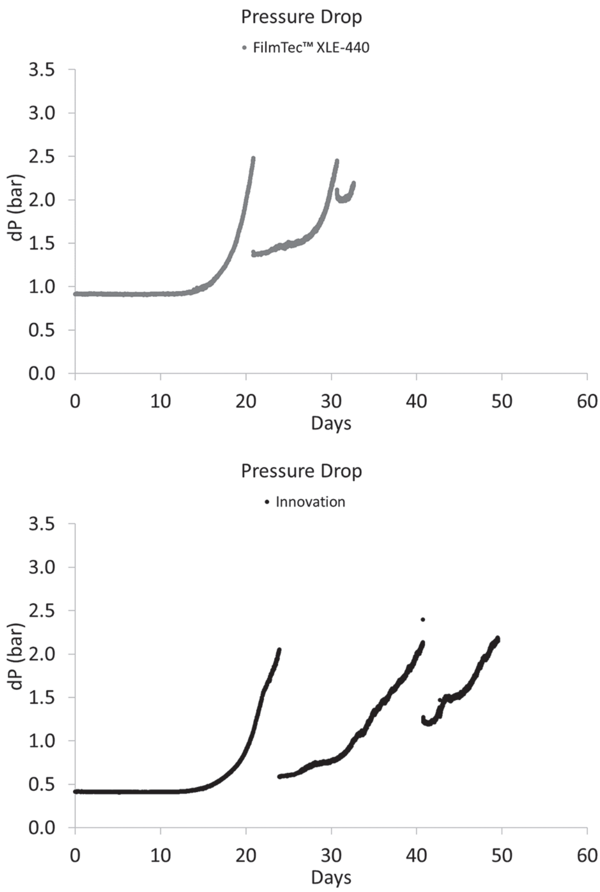


Figure 23: More operating time achieved thanks to a fouling-resistant membrane.

Chapter 13 – Limiting nutrients to prevent biofouling in brackish water

Biofouling in brackish water can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

The same biofouling prevention technology can reduce total suspended solids.

This biofouling prevention system uses biomass, not a biofilm, to prevent biofouling.

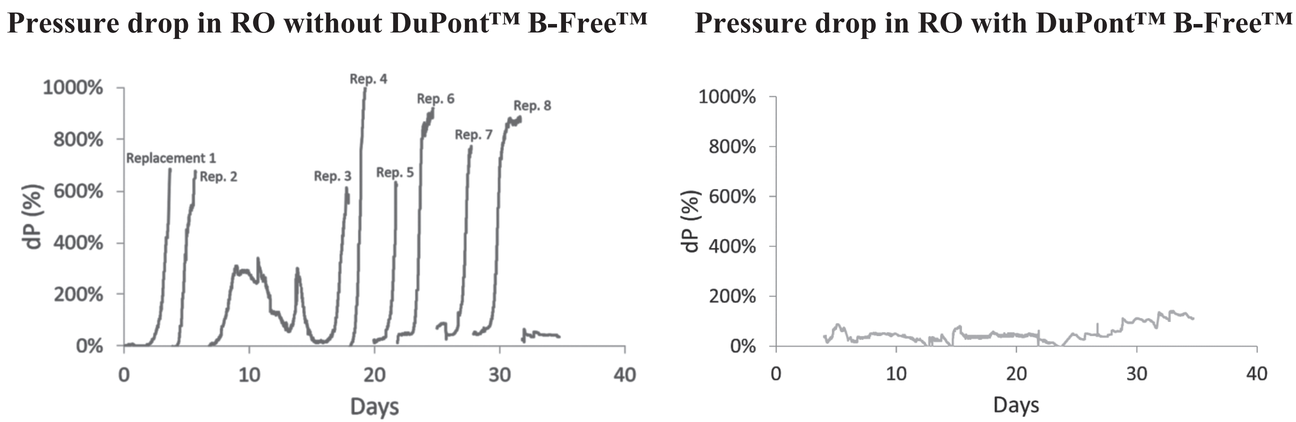


Figure 24: Reverse osmosis pressure drop without (left) and with (right) DuPont™ B-Free™.

Chapter 14 – Limiting nutrients to prevent biofouling in wastewater

Biofouling in wastewater can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

The same biofouling prevention technology can reduce cartridge filter replacements.

The same biofouling prevention technology can reduce organic compounds.

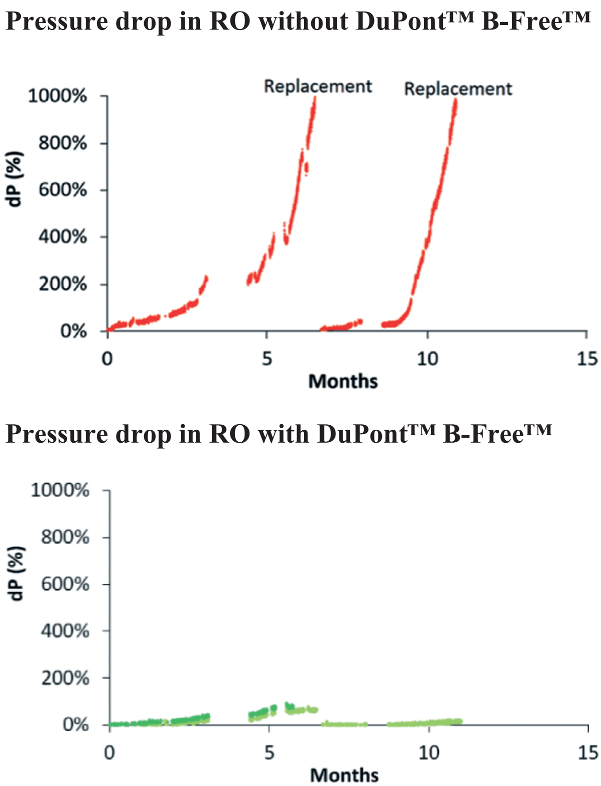


Figure 25: Reverse osmosis pressure drop without (top) and with (bottom) DuPont™ B-Free™.

Chapter 15 – Limiting nutrients to prevent biofouling in seawater: part 1

Biofouling in seawater can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

The same biofouling prevention technology can reduce cartridge filter replacements.

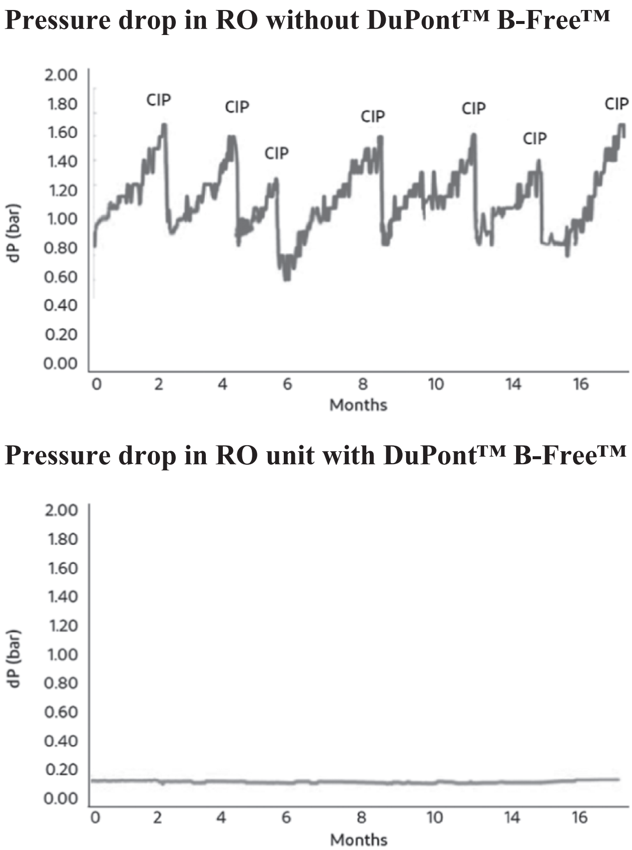
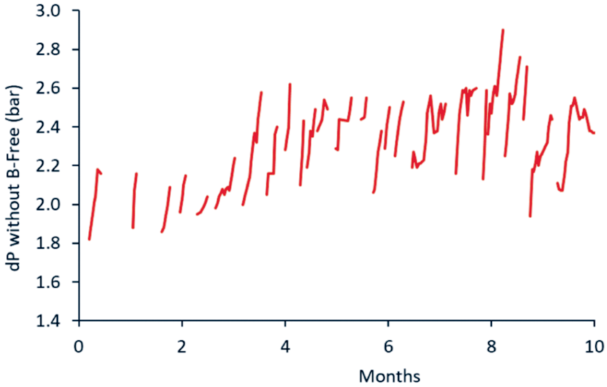


Figure 26: RO pressure drop evolution in seawater test.

Chapter 16 – Limiting nutrients to prevent biofouling in seawater: part 2

Biofouling in seawater can be effectively limited by restricting the bioassimilable nutrients that reach the reverse osmosis system.

Pressure drop in RO without DuPont™ B-Free™



Pressure drop in RO with DuPont™ B-Free™

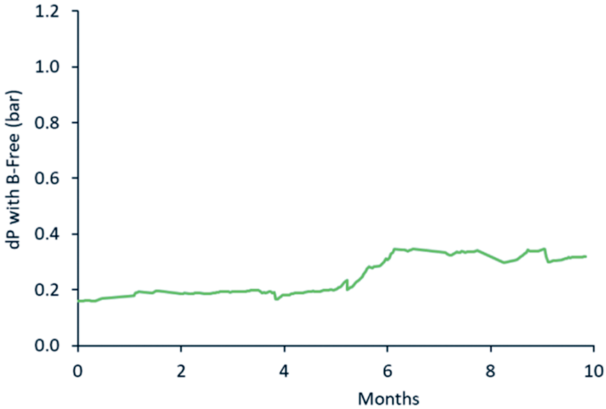


Figure 27: Cartridge filter pressure drop evolution in seawater test.

Chapters summary

Chapter 1 – Reverse osmosis fundamentals

This chapter explains the fundamental equations of reverse osmosis membranes. It details why its adoption has increased over the years and what its main advantages are compared to thermal processes. It explains what a reverse osmosis membrane is and what it is made from. It provides an overview of the main equations to calculate the osmotic pressure, the water flux, and the salt passing across a reverse osmosis membrane, and the main equations used to evaluate a reverse osmosis system. It also explains how to normalize plant operating data and why normalization matters to properly assess an installation's performance. These equations are the normalized permeate flow, the normalized salt rejection, and the normalized pressure drop. The main types of fouling found in a reverse osmosis membrane are detailed. These are biological fouling, also known as biofouling, organic fouling, inorganic fouling, also known as scaling, and particulate fouling.

Chapter 2 – Biofouling fundamentals

This chapter explains the fundamentals of organic and biological fouling. Biofouling is characterized by an initial phase of a flat pressure drop increase over time, followed by a second phase consisting of exponential growth. Organic fouling is characterized by a sudden loss in normalized permeate flow that later tends to stabilize and plateau. This phase is typically characterized by a flat pressure drop if no biofouling occurs at the same time. Special emphasis is placed on understanding which factors most influence the development of biofouling, along with explaining the strategies that can be taken to prevent it. This is illustrated by the concept of the biofouling triangle, where three key factors in biofouling development are identified. These factors are temperature, which promotes bacterial growth; bacteria availability, which is needed for bacteria to reproduce; and nutrient availability, which is needed for bacteria to grow and reproduce, and comprises assimilable organic nutrients such as carbon, nitrogen, and phosphorus, together with oxygen, which is used for bacteria to grow.

Chapter 3 – Membrane fouling simulators: a quick tool to study biofouling and why biofouling does not depend on flux

This chapter presents a research tool, the Membrane Fouling Simulators. These small assets are a quick way to study biofouling. In this chapter, it is explained how these tools are representative of the biofouling that occurs in larger installations. This is demonstrated through validation with two different plants. This tool is used to study new feed spacers with the potential to reduce the impact of biofouling in reverse osmosis membranes. This chapter also outlines that permeate flux does not appear to be a relevant parameter for biofouling development, as Membrane Fouling Simulators operate under no permeate water flux across the membrane and are able to fully mimic the biofouling development.

Chapter 4 – The importance of the feed spacer to prevent biofouling

This chapter outlines the importance of the feed spacer in preventing biofouling. This is proven across multiple experiments, where it can be seen that without a feed spacer, biofouling hardly develops. This chapter also outlines how different membranes with different properties can mitigate the biofouling development in a reverse osmosis membrane element. It is hypothesized that the feed spacer plays a crucial role in preventing biofouling, as biofouling needs a place to adhere and grow that is sheltered from the water flow but still receives enough nutrients to sustain itself and grow.

Chapter 5 – The effect of the temperature and development of quick biofouling test

This chapter outlines the importance of temperature in developing biofouling, where it is shown that when the temperature dropped below 17 °C, biofouling developed at a much slower pace. It also validates and establishes a quick biofouling test where dosing essential bioassimilable nutrients made of carbon, nitrogen, and phosphorus speeds up the development of biofouling. Finally, this quick biofouling test was adapted so that biofouling could properly be studied at lower temperatures. Dosing nutrients can be used to accelerate the biofouling period and enables better study of biological fouling.

Chapter 6 – Differentiating between biofouling and organic fouling during operation

This chapter compares two different membranes. Both membranes are compared side by side during an initial organic fouling phase, followed by a second biological fouling phase. In these two phases, it can be seen how the fouling-resistant membrane allows for improved fouling resistance as it is able to withstand a lower water permeability loss over time.

Chapter 7 – Differentiating between biofouling and organic fouling on a membrane surface

This chapter outlines how biofouling can be distinguished from organic fouling when a membrane is analyzed together with the operating parameters. It can be seen that biofouling is identified by a significant increase in pressure drop. This is later confirmed during the membrane autopsy, when it is verified that the majority of the fouling present on the membrane is composed of exopolymeric substances (EPS). In contrast, organic fouling is identified by hardly increasing the pressure drop and having a smaller percentage of EPS in its total fouling amount when the membrane is analyzed. This is explained by the fact that when bacteria build biofilms, the biofilm, which is mainly composed of EPS, blocks the feed-concentrate channel, leading to a pressure drop increase. On the contrary, organic fouling is characterized by organic matter adsorbing to the membrane, leading to a sharp normalized flux decline (higher energy consumption), but not blocking the feed-concentrate channel and therefore not contributing to a pressure drop increase. Additionally, these organics might come from sources other than the biofilm, leading to a smaller percentage of EPS in the overall fouling composition.

Chapter 8 – Biofouling starts to develop before pressure drop starts to increase

This chapter shows how, despite that initially a biofilm might not be noticed by an increase in pressure drop over time, it might have already started forming. This is confirmed by the measurement of ATP accumulation on the membrane, where it is observed that ATP, which represents bacteria, starts increasing very fast at the beginning of the trial, when the pressure drop still remains quite flat. This research also shows how TOC starts accumulating very fast on the membrane at the beginning of the trial. This indicates the beginning of the first organic fouling period. This TOC accumulation on the membrane matches well with the mechanism by which biofilms are formed, as for a biofilm to start growing, it needs a substrate. This is referred to as the conditioning layer. This chapter also shows how ATP measurement on a membrane might be used as an early indicator of biofouling, pointing to a way to identify when a biofilm is starting to form, before this early biofilm formation leads to a biofilm that is big enough to start causing a decrease in pressure drop, therefore leading to the problem of biofouling in a reverse osmosis system. ATP starts to accumulate after TOC has already accumulated.

Chapter 9 – Biofouling mainly happens in the lead elements

This research shows how a smart distribution of feed spacers in a pressure vessel can reduce biofouling. It also shows that biofouling mainly develops in the lead elements. It also highlights the difficulty in cleaning to the initial pressure drop once biofouling develops. It shows that it is very difficult to fully remove a biofilm inside a reverse osmosis membrane. It also points out that caustic cleaning provides the highest cleaning effectiveness. It also shows that biocide cleaning can reduce the number of bacteria in a biofilm but does not help in preventing biofouling. It is also observed that biofouling can be easily brushed or removed by stirring in a beaker from a membrane and feed spacer. Finally, this trial shows the two classical fouling phases: the first organic fouling phase and the later biofouling phase that grows over the already organically fouled membrane.

Chapter 10 – Biocides do not fully prevent biofouling

This chapter shows how shock-dosing a non-oxidizing biocide initially helps delay biofouling, but after a certain amount of time, biofouling starts to develop normally. It can also be seen the role that a fouling-resistant membrane has in experiencing a smaller loss of water permeability over time. It is hypothesized that, despite the biocide being effective in eliminating bacteria, after the biofilm has grown enough, bacteria can shelter in the EPS, and this is when the biocide stops being effective. Dosing biocide is a useful method to study the first organic fouling part without biofouling interference.

Chapter 11 – Visualizing biofouling on the membrane surface

This chapter explains how biofouling can be easily visualized and quantified on a membrane surface. This technique is used to demonstrate that biofouling mainly grows on the first elements in a pressure vessel, where it can be seen which are the main areas that biofouling colonizes, as well as what percentage of the membrane is occupied by biofouling.

Chapter 12 – Why preventing biofouling matters

This chapter provides an example of why designing a fouling-resistant reverse osmosis membrane matters. In this particular case presented, it can be seen that thanks to the enhanced fouling-resistant properties of the newly developed element, chemical cleanings due to biofouling can be reduced by 30%, therefore extending the period the membranes can operate without cleanings by 56%. At the same time, energy consumption is reduced by 10%, while the feed-concentrate pressure drop is reduced by 55%.

Chapter 13 – Limiting nutrients to prevent biofouling in brackish water

This chapter explains how biofouling can be effectively prevented by adding a pretreatment step between the ultrafiltration and the reverse osmosis system. This pretreatment is called DuPont™ B-Free™ and focuses on limiting the nutrients that can reach the downstream reverse osmosis system, so that biofouling does not develop in the reverse osmosis system. Instead of biofouling growing in the lead elements of the reverse osmosis system, biofouling grows in this pretreatment, where it can be easily controlled and cleaned, and where its pressure drop performance can always be restored to its initial values. This chapter also showcases how this pretreatment technology can reduce up to 99.5% of suspended solids. Additionally, the relationship between biomass thickness and additional pressure drop increase is also established.

Chapter 14 – Limiting nutrients to prevent biofouling in wastewater

This chapter explores the effective prevention of biofouling by incorporating a pretreatment step between the ultrafiltration and reverse osmosis systems. This pretreatment stage is designed to minimize the nutrients available to the reverse osmosis system, thereby preventing biofouling from developing downstream. Unlike the biofouling growth typically observed in the lead elements of reverse osmosis systems, as discussed in previous chapters, biofouling is redirected to the pretreatment stage. Here, it can be more easily managed and cleaned, ensuring the system's pressure drop performance is consistently restored to its original levels. Additionally, the chapter demonstrates how this approach reduces the replacement frequency of cartridge filters. The technology behind this innovation, DuPont™ B-Free™, is shown to effectively prevent biofouling in wastewater environments while also reducing the risk of organic fouling in reverse osmosis systems.

Chapter 15 – Limiting nutrients to prevent biofouling in seawater: part 1

This chapter discusses a method to effectively prevent biofouling by incorporating a pretreatment step between the ultrafiltration and reverse osmosis systems. The purpose of this pretreatment is to limit the nutrients reaching the reverse osmosis system, thereby inhibiting the development of biofouling within it. Instead of biofouling occurring in the lead elements of the reverse osmosis system, as detailed in previous chapters, this process shifts biofouling to the pretreatment stage. In this controlled setting, biofouling can be easily managed, cleaned, and its pressure drop performance reliably restored to original levels. The chapter also highlights how this approach reduces the frequency of cartridge filter replacements. Using the example of a desalination plant in the Canary Islands, Spain, which is known for its severe biofouling issues, it demonstrates the effectiveness of DuPont™ B-Free™ technology in mitigating this challenge.

Chapter 16 – Limiting nutrients to prevent biofouling in seawater: part 2

This chapter provides another example of how the DuPont™ B-Free™ pretreatment technology is able to prevent biofouling by limiting the nutrients that reach the downstream reverse osmosis membranes in a seawater desalination plant in the United Arab Emirates.