REMOVAL OF PHARMACEUTICAL ACTIVE COMPOUNDS FROM DRINKING WATER USING NANOFILTRATION TECHNOLOGY: COMPARATIVE STUDY OF DIFFERENT MEMBRANES.

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Abstract

The presence of emerging contaminants in drinking water supplies, wastewater effluents and the environment is a matter of concern. Advanced treatment technologies are required to efficiently remove the wide variety of organic compounds with different physico-chemical characteristics that can be found in the aquatic environment. Membrane technology, which can improve the removal of pharmaceutical active compounds (PhACs) among other types of emerging contaminants, is an alternative to conventional treatments of drinking water. In this study, the removal of ibuprofen, diclofenac and carbamazepine in drinking water was investigated using three nanofiltration (NF) membranes (AFC80, AFC40 and AFC30) in a patented pilot-scale plant. Experiments were performed at initial PhAC concentrations of 50µg/L at 1000L/h (Concentrate Flow) and 30°C. The influence of transmembrane pressure on the permeate flux and on the retention of the selected compounds was evaluated. PhCA retention was estimated by performing a quantitative analysis of the compounds by ultra-high performance liquid-chromatography coupled to tandem mass spectrometry (UHPLC-MS/MS). The membranes were characterized in detail using Atomic Force Microscopy (AFM), a retention test of different neutral solutes and liquid displacement porosity. X-ray photoelectron spectroscopy (XPS) allowed the material composition of the active layer of nanofiltration (NF) membranes to be determined accurately.

The rejection of ibuprofen, diclofenac and carbamazepine by NF membranes was highly efficient, exceeding 95% in most cases. Size exclusion was found to be the prevailing rejection mechanism of the PhACs by the AFC80 membrane (neutral), while in AFC40 and AFC30 (negative surface charge) rejection was associated with the combined action of electrostatic interactions (between the membrane surface and PhAC charge) and size exclusion.
Keywords: water treatment, Nanofiltration, PhAC rejection, UHPLC/MS/MS, AFM, XPS.

1. Introduction

Conventional treatments commonly applied to drinking water are not designed to remove emerging contaminants that might be present in water sources, typically at (sub)-ppb levels. Consequently, these types of contaminants might be present in drinking water unless a highly efficient removal system is applied (Boyd, Reemtsma et al. 2003, Vulliet, Cren-Olive´ et al. 2009, Kumar and Xagoraraki 2010, Sodré Fernando F 2010, Yang, Flowers et al. 2011, Houtman, Kroesbergen et al. 2014, Kosma, Lambropoulou et al. 2014). It is therefore necessary to implement advanced treatment technologies to guarantee the required water quality. This trend is reflected by the increasing number of studies reporting on the application of different water treatments in recent years (Boyd, Reemtsma et al. 2003, Bolong, Ismail et al. 2009, Yang, Flowers et al. 2011).

In last years, research has been performed with promising results regarding the applicability of membrane technology for the removal of organic materials and emerging contaminants, specifically PhACs in wastewater treatment processes (Yoon, Westerhoff et al. 2006, Yoon, Westerhoff et al. 2007, Arnal, Garcia-Fayos et al. 2009) included in membrane technology, nanofiltration (NF) membranes have proven to be successful at the elimination of a large number of organic compounds. However, the majority of these studies have been carried out on a small scale and generally in synthetic waters prepared in the laboratory (Van der Bruggen and Vandecasteele 2003, Yoon, Westerhoff et al. 2006, Verliefde, Cornelissen et al. 2007, Yoon, Westerhoff et al. 2007).

In this work the rejection of 3 PhACs was evaluated (Ibuprofen (IBU), diclofenac (DIC) and carbamazepine (CBZ)). Known concentrations of these compounds were added to drinking water. The treatment of drinking water was carried out using a nanofiltration pilot scale plant (Otero Hermida 2008). The study was carried out using three different nanofiltration membranes (AFC30, AFC40 and AFC80). The effect of pressure on permeate flow and rejection was evaluated while both the temperature and concentrate flow remained constant. It was determined whether the main factor affecting separation was size exclusion or the repulsion of electrostatic charge between the surface of the membrane and the PhACs under study. The determination of PhACs was made by ultra-high performance liquid chromatography (UHPLC) coupled to tandem mass spectrometry (MS/MS). This technique is the most commonly used at present for determination of emerging contaminants at low concentrations due to its robustness, excellent sensitivity and selectivity (Gracia-Lor, Martínez et al. 2012, Hernández, Ibáñez et al. 2014, Boix, Ibáñez et al. 2015).

2. Materials and methods

2.1. Materials

2.1.1. Water source

The filtration experiments were carried out using drinking water. At the beginning of the experiment, it was confirmed that the compounds to be studied (IBU, DIC and CBZ) were not present in this water.

2.1.2. Chemicals
For removal experiments, a mix of 100 mg/L of 3 PhACs was prepared with methanol. For the analytical measurements, working solutions were subsequently diluted with HPLC-grade water for the preparation of calibration standards (2.5-5-10-50-100 µg/L). All standard solutions were stored in amber glass bottles at −20 °C. Oasis HLB (60 mg) cartridges from Waters (Milford, MA, USA) were used for solid-phase extraction (SPE).

### 2.1.3. Membranes

Three commercial NF membranes: AFC80, AFC40 and AFC30 were used. All were of the thin film composite (TFC) type with an active layer of aromatic polyamide on a porous support of polysulfone. The studied membranes were prepared in 18 tubes connected in a series using a type B1 module. Each tube had an internal diameter of 12.8 mm and a length of 1.2 m, which gave a total filtration area of 0.864 m². PCI Membranes (Paterson Candy International-Ltd., UK) supplied both the module and the membranes (Table 1).

**Table 1. PCI Nanofiltration membrane characteristics**

<table>
<thead>
<tr>
<th>Membrane</th>
<th>Material</th>
<th>Max. pH Range</th>
<th>Maximum Pressure (bar)</th>
<th>Max. Temp (°C)</th>
<th>Hydropilicity 1 to 5</th>
<th>Solvent Resistance 1 to 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC80</td>
<td>Polyamide film</td>
<td>1.5-10.5</td>
<td>60</td>
<td>70</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>AFC40</td>
<td>Polyamide film</td>
<td>1.5-9.5</td>
<td>60</td>
<td>60</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>AFC30</td>
<td>Polyamide film</td>
<td>1.5-9.5</td>
<td>60</td>
<td>60</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

### 2.2 Equipment and experimental protocol

The Universal Mobile Membrane Testing Pilot Plant with a Pressure Gradient, (PPUMEMGP), testing equipment used, was developed and patented by the Membrane Filtration Processes Engineering group of the University of Cantabria (IPFM-UC) (patent N° 2296446 (Otero Hermida 2008)) (Figure 1).

The experiment was carried out in three stages. First each membrane was characterised using a permeability test with pure water. Next, salt rejection was determined employing solutions in pure water with NaCl at 0.01M and the corresponding isotonic concentrations of Na₂SO₄ and CaCl₂ (0.0077M and 0.0073M respectively). In this way the surface charge of the membranes could be established (Weast 1983-1984). Finally, the rejection of the PhACs was evaluated.

The supply water was prepared by fortifying 118L of drinking water with a mix of the 3 PhACs until a concentration of 50 µg/L of each compound was reached. All experiments were carried out at total reflux, where the concentrate, recirculation and the permeate return to the supply tank (Figure 1). All tests were carried out at 30 ± 0.5°C with a concentrate flow of 1000L/h. The pressure was varied in increments of 10 from 10 to 50 bar in order to establish its effect on the permeate flow and the rejection. Samples were then taken from the tank and permeate for analysis the PhAC concentration.
2.3.1 Sample procedure and analysis

For the analysis of the PhACs, solid phase extraction (SPE) of 100 mL of sample was performed using Oasis HLB cartridges to pre-concentrate the analytes. This was followed by elution with 5 mL MeOH, evaporation to dryness and reconstitution of the extract in 1mL MeOH–water (10:90 v/v). Finally, 100 µL were injected into the an Acquity UPLC system coupled to a TQD (triple quadrupole) mass spectrometer with an ortho-gonal Z-spray-electrospray (ESI) (Waters Corp., Milford, MA, USA)UHPLC–MS/MS system. The UHPLC-MS/MS method applied was based on one previously developed and validated by Gracia-Lor et al. (Gracia-Lor, Martínez et al. 2012) with a modification in the mobile phase gradient to shorten the chromatographic run time.

2.4. Membrane characterization

2.4.1. Atomic force microscopy (AFM)

AFM was performed using a MultiMode Scanning Probe Microscope Nanoscope IIIA from Digital Instruments provided with an AS-10 E Scanner. For AFM exploration, the samples were left in ambient air and the tapping mode (intermittent contact) was used with an EBD (electron beam deposited) sharpened tip made by Nanotoools® with length of 1000 nm, a point angle of less than 10° and an end curvature radius below 5 nm, in accordance with the manufacturer’s specifications. The tip oscillated at a natural frequency of 300 kHz. The AFM images were processed by using a fast Fourier transform (FFT) filtering procedure (Otero, Lena et al. 2006, Otero, Lena et al. 2008, Otero, Mazarrasa et al. 2008)

2.4.2. X-ray photoelectron spectroscopy (XPS)
Three commercial nanofiltration membranes (AFC30, AFC40 and AFC80) were characterized by X-ray photoelectron spectroscopy. XPS spectra were recorded with an Omicron spectrometer equipped with an EA-125 hemispherical electron multichannel analyzer and unmonochromatized Mg Kα, an X-ray source at 150W and a pass energy of 20 eV. The samples were pressed into a small pellet of 15mm in diameter, mounted on the sample holder and put in the chamber where they were degassed for 6–8 h in order to achieve a dynamic vacuum below $10^{-8}$ Pa prior to analysis. The resulting spectral data were analyzed using CASAXPS software and a RSF database by peak fitting after Shirley background correction.

2.5. Performance evaluation of TFC NF membranes

The behavior of the NF membranes was determined by evaluating the flow of the permeate ($J_P$, L.m$^{-2}$.h$^{-1}$) and the rejection (R, %) of the studied compounds, as well as the permeability for the pure water ($A_{PW}$). The productivity of the membrane was achieved by calculating the coefficient of permeability ($A_W$), which is a characteristic parameter of the membrane under any given working conditions (Lonsdale, Merten et al. 1965, Merdaw, Sharif et al. 2010). The rejection of all of the studied compounds was calculated according to the following equation:

$$R (\%) = \frac{(C_T-C_P)}{C_T} \times 100$$

Where $C_T$ and $C_P$ are the concentrations of each compound in the supply tank and the permeate respectively.

3. Results and discussion

3.1 Membrane characterization

3.1.1. Atomic force microscopy (AFM)

The AFM results for the nanofiltration membranes allowed the pore size distribution and the median pore radius to be determined. Values of 0.51, 0.44 and 0.38 nm were obtained for the AFC30, AFC40 and AFC80 membranes respectively, giving a pore size sequence of AFC30>AFC40>AFC80 (Otero, Lena et al. 2006, Otero, Lena et al. 2008, Otero, Mazarrasa et al. 2008).

3.1.2. X-ray photoelectron spectroscopy (XPS)

The chemical composition of the surface of the TFC NF membranes were analysed by XPS (Table 2). The atomic concentrations observed for C, O and N are typical of the active layer of aromatic polyamide (Tang, Kwon et al. 2009, Wei, Wang et al. 2010). The active surface of the AFC30 membrane shows a different chemical composition, with a relatively low quantity of nitrogen.

<table>
<thead>
<tr>
<th>Membrane</th>
<th>% at C</th>
<th>% at O</th>
<th>% at N</th>
<th>C/O</th>
<th>C/N</th>
<th>O/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC30</td>
<td>65.83</td>
<td>32.27</td>
<td>1.90</td>
<td>2.04</td>
<td>34.65</td>
<td>16.98</td>
</tr>
<tr>
<td>AFC40</td>
<td>69.11</td>
<td>23.70</td>
<td>7.19</td>
<td>2.92</td>
<td>9.61</td>
<td>3.29</td>
</tr>
<tr>
<td>AFC80</td>
<td>67.92</td>
<td>25.48</td>
<td>6.60</td>
<td>2.66</td>
<td>10.29</td>
<td>3.86</td>
</tr>
</tbody>
</table>

Table 2. XPS results of the membrane surface
The negative surface charge of the active layer of the nanofiltration membranes may come from the presence of deprotonated carboxylic acids ($\text{COOH} \rightarrow \text{COO}^-$) and the positive charge may be a result of protonation of the amino functional groups ($\text{NH}_2 \rightarrow \text{NH}_3^+$) (Petersen 1993, Elimelech, Chen et al. 1994, Childress and Elimelech 1996, Childress and Elimelech 2000).

The large proportion of oxygen and the low proportion of nitrogen in the AFC30 membrane would suggest it has a strongly negative character compared with the AFC40 and AFC80 membranes. From the results obtained we can initially assume that the negative charge sequence is AFC30>AFC40. In contrast, the AFC80 membrane shows an equilibrium between the two charged functional groups, which means it essentially behaves like an almost neutral membrane (Tang, Kwon et al. 2009).

3.2. Evaluating the performance of the TFC NF membranes

3.2.1 Pure water permeability ($A_W$)

The permeability was determined as the flow of pure water that passes through the membrane against pressure. It depends on the pore size, porosity and thickness of the active layer. The permeability for the studied membranes in decreasing order is AFC30>AFC40>AFC80, in accordance with their $A_W$ values of 5.62, 4.12 and 1.81 ($\text{L.h}^{-1}.\text{m}^{-2}.\text{bar}^{-1}$) respectively. This indicates that the AFC30 membrane has the greatest pore size and therefore presents a greater productivity in terms of permeate flow.

3.2.2 Electrolyte solution retention

To determine the surface charge of the membranes, Peeters et al proposed an experimental method that calculated the charge according to the rejection of three different salts studied individually. In this case NaCl, CaCl$_2$ and Na$_2$SO$_4$ were used (Peeters, Boom et al. 1998, Baker 2012), the AFC30 membrane is clearly classified as a negatively charged membrane. Regarding the AFC40 membrane rejection was a little less for NaCl than for CaCl$_2$, which, according to the method employed, categorizes it as a less negative membrane. For the AFC80 membrane, the order of salt rejection was according to molecule size: Na$_2$SO$_4 \approx$ CaCl$_2 >$NaCl. This assumes that the membrane is neutral, meaning that rejection will not be affected by the charges of the compounds in the solution. In principle, these results are in agreement with the experimental data given by the XPS analysis.

3.2.3.2 Retention of PhACs by nanofiltration

According to the characterization of the membranes, AFC80 does not possess a surface charge and has the lowest pore size (lower $A_W$), meaning that the rejection mechanism is essentially size exclusion. In the case of the negatively charged AFC40 and AFC30 membranes, compound retention does not only occur via size exclusion but also via electrostatic interactions between the charged surface of the membrane and the charge of the compounds at the working pH (around 8).

Both DIC and the IBU are negatively charged compounds at the working pH (Verliefde, Cornelissen et al. 2008, Vergili 2013). These compounds were strongly retained in the AFC80 membrane (neutral) and (to a lesser extent, but in a similar way) in the negatively charged AFC30 and AFC40 membranes. The rejection of the DIC and IBU was slightly greater in AFC40 than in AFC30 (Figures 2a and 2b), which was unexpected due to the greater negative charge on the surface of AFC30 (Figures 2a and 2b). This seems
to be related to the presence of Ca\textsuperscript{2+} ions in the water matrix, as can be seen below.

CBZ, a neutral compound, has a rejection of around 98% in the AFC80 membrane. In the AFC40 and AFC30 membranes the retention is almost the same, around 90 to 92% (Figure 2c), but less in comparison to IBU and DIC. This behaviour is due to the relationship between the surface charge of the membranes and the charge and size of the contaminants.

For the AFC40 and AFC30 membranes, the order of retention is (%R)DIC>(%R)IBU>(%R)CBZ. This behaviour can be explained because in these membranes separation is conducted by the combined action of the effect of size exclusion and electrostatic interactions with the membrane surface.

The negatively charged AFC40 and AFC30 membranes mainly reject IBU and DIC, which are negatively charged at the working pH. The rejection of CBZ is less (greater MW) because this compound does not

**Figure 2.** Rejection vs pressure for all membranes a) DIC, b) IBU and c) CBZ.
possess charge and has a significant dipolar moment that favours passage through the membranes (Van der Bruggen, Schaep et al. 1998, Kimura, Toshima et al. 2004). These results indicate that the predominant mechanism in the separation of the AFC40 and AFC30 membranes for compounds of a similar molecular weight is retention by charge repulsion.

Regarding the variable of operational pressure, for the AFC40 and AFC30 membranes there is a slight tendency for the retention to decrease with an increase in pressure (Figure 3). This can be explained by the fact that an increase in pressure causes an increase in concentration polarization due to the conduction of the PhACs towards the surface of the membranes, causing a decrease in the retention of the compounds (Semião 2011). However, the decrease in rejection is low for both membranes, in the order of 1 to 4%.

Figure 4. Rejection of PhACs in a) AFC80, b) AFC40, c) AFC30

4. Conclusions

High rejection percentages (% R) were obtained for the selected PhACs under the test conditions (pH 8, 1000L/h, 30°C and 50 µg/L). The NF membranes evaluated were adequate for elimination of these contaminants, with rejections between 88 and 98% for CBZ and greater than 96% for IBU and DIC. It was also shown that in the AFC80 membrane, rejection occurred mainly because of the difference in size, while in the AFC40 and AFC30 membranes separation was due to the combined effect of size exclusion.
and interactions between the surface and the ionic forms of the compounds at the pH of the water sample (pH 8).

Given the high level of rejection of the three NF membranes, the one to be used for water treatment should be chosen based on the removal and productivity needs of the permeate flow. If the aim is to achieve the greatest rejection regardless of the permeate flow, the AFC80 membrane seems the most appropriate option. However, if a high retention is desired and at the same time a greater permeate flow, AFC30 would be the best choice as it allows the greatest quantity of treated water to be obtained per unit of time and area.

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6. References


