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Techno-economic assessment of decentralized polishing schemes for municipal water reclamation and reuse in the industrial sector in costal semiarid regions: The case of Barcelona (Spain)

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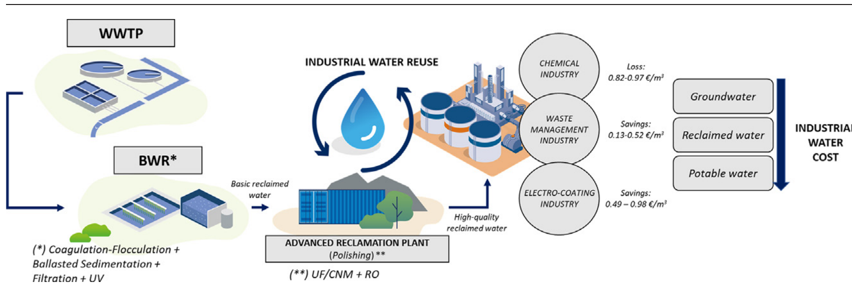
HIGHLIGHTS

- Demonstration at pilot-scale of two pre-treatments for RO: (i) UF and (ii) CNM.
- Permeability decline of 5% in RO was observed when was fed with CNM effluent.
- Triazine pesticides removal of 67% and 97% were found in the CNM stage.
- Cost curves (CAPEX and OPEX) calculation for three different technologies.
- Water reuse can provide savings between 0.13 and 0.98 €/m^3 for evaluated industries.

GRAPHICAL ABSTRACT



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ABSTRACT

This study demonstrates the techno-economic reliability of an innovative fit-for-use treatment train to boost municipal reclaimed water reuse fore industrial uses in the Barcelona Metropolitan Area (BMA). The relatively high conductivity (2090 μS/cm) and hardness (454 mg/L) of reclaimed water in the BMA (e.g. Water Reclamation Plant (WRP) of El Baix Llobregat, Barcelona, Spain), together with the restrictive water quality demands in industrial uses, claims for the implementation of advanced reclamation schemes based on desalination technologies such as reverse osmosis (RO). The study assesses the benefits of two potential pre-treatments of the RO stage: (i) ultrafiltration (UF) or (ii) an innovative high-performance nano-structured polymeric adsorbent (CNM); in which a permeability decline of 5% was observed when CNM was used as a pre-treatment, while a stable permeability of RO was found when was fed by the UF effluent. On the other hand, generic cost curves have been calculated for the technologies evaluated and were applied to estimate capital and operational expenditures (CAPEX and OPEX) for the scale-up in three different industrial sites (e.g., chemical, waste management and electro-coating industries). The economic assessment indicates that the use of municipal reclaimed water is economically competitive in front of the use of tap water in the BMA, providing savings between 0.13 and 0.52 €/m^3 for the waste management industry and between 0.49 and 0.98 €/m^3 for the electrocoating industry. On the other hand, the use of groundwater in one of the industrial sites and its relatively low cost implied that, although it is necessary a RO, the current cost of water is significantly lower.

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1. Introduction

Water scarcity represents a growing challenge in the EU coastal regions, especially in the Mediterranean area, and it has been accentuated in recent decades due to extreme effects of climate change in terms of more frequent and prolonged droughts. This issue has evidenced the need to resort to more resilient strategies and incorporate alternative water resources in the water cycle.

Water reuse has become another key component for water planning together with freshwater resources and seawater desalination, allowing the increase in freshwater availability, and saving conventional resources for environmental maintenance and drinking water supply. In different water stressed regions, water reuse for non-potable uses has been proved from an economic and environmental point of view, as the most sustainable alternative to the use of freshwater resources (Allen et al., 2017). This is due to overexploitation or contamination of groundwater (e.g., nitrates and salinity), and the need to purchase imported water for potable water supply. Examples can be found in coastal Spanish regions such as Barcelona, Alicante, or Murcia, which present higher energy consumption and operation and maintenance (O&M) costs in water treatment than other regions, and water reclamation represents an attractive opportunity from a cost perspective (AEAS, 2017).

Industrial water consumption in Europe represents the 32% of total water abstractions in the EU (EEA, 2017). The need of industrial users to guarantee their production and protect themselves against water shortages has raised their interest in boosting water reuse projects. Nevertheless, despite its demonstrated benefits, water reuse is still far from its potential. The European Commission reported that only 2% of the total treated wastewater in Europe was reclaimed and reused (964 Hm^3/year) (European Commission, 2021). Specifically, in Spain, the total water reclamation is estimated in 400 Hm^3/year (Allen et al., 2017) and the use of municipal reclaimed water to cover industrial needs accounts to 12% of the total reclaimed water volume.

On the other hand, the reclamation and reuse of municipal wastewater faces different local transversal challenges such as social perception and the lack of economic and governance successful models. From the strictly techno-economic point of view, it is necessary to ensure the water quality demanded by both regulation and end-users and be able to demonstrate efficient fit-for-use water reclamation trains. While conventional secondary and tertiary treatment trains have demonstrated consistent efficiency in organic matter and nutrients removal, salinity and some organic micropollutants (OMP) remain in the treated effluents and its elimination require the application of advanced technologies.

Salinity and hardness are highly restricted in industrial water uses, especially for sensitive applications such as boiler feed, closed-loop cooling circuits or process water, in which scaling and corrosion are the main concerns in the main industrial sectors (e.g. Chemical, Oil & Gas, Mining & Metallurgy, Automotive, Food & Beverage, among others) (Barot et al., 2020; Löwenberg et al., 2015). Moreover, the presence of OMP in reclaimed water effluents represents a risk in terms of its concentration in the water cycle since these compounds are reincorporated again and again in the wastewater treatment plants (WWTPs).

The application of Reverse Osmosis (RO) membranes is relatively extended in industrial water supply in order to reduce total dissolved solids (TDS) from both groundwater or tap water sources. This allows one to directly obtain a suitable water that meets with quality requirements. Borsani et al. (1996) assessed the use of RO to provide process water in a steel making plant in Woljsky (Volgograd, Russia). Additionally, Alsarayreh et al. (2021) and Al-Obaidi et al. (2021) assessed the performance of medium sized RO plants to supply water for industrial applications.

Quevedo et al. (2012) investigated the use of RO for surface and groundwater water make-up for industrial water supply, as well as its pre-treatment needs. Nevertheless, when municipal reclaimed water is intended to be used for industrial applications, the selection and implementation of the correct pre-treatments for RO results even more challenging due to reclaimed water physico-chemical properties. Membrane filtration systems such as Microfiltration (MF) or Ultrafiltration (UF) are commonly applied as pre-treatment requirement to ensure the removal of particulate inorganic and organic matter and ensure a Silt Density Index (SDI) below 3 (Touati et al., 2018). In addition, media filters could be used and when based on anthracite or granular activated carbon (GAC) they provide the possibility of reducing the levels of dissolved organic matter (DOC) (Kavitha et al., 2019). In this direction, some authors have evaluated novel materials with claims on nanostructured properties that may act as high efficiency adsorbents (Moradi and Sharma, 2021). Some of them, in base to a polymeric structure, could be regenerated chemically on-site and then overcome the limitation of GAC that only could be thermally regenerated off-site (Larasati et al., 2021). As an example, Lewatit® AF 5 a microporous carbonaceous sorbent in bed form, derived from a synthetic polymer with a high surface area of 1300 m^2/g, has been designed for downstream process separation and purification (Reczek et al., 2020).

The implementation of advanced reclamation schemes to supply municipal reclaimed water for industrial uses is not new and several successful case studies can be found at worldwide level (BlueTech, 2016). In North-America, The Edward C. Little Water Recycling Facility (ECLWRF) is the main water reuse system of West Basin Municipal Water District (California), with a nominal capacity of 151,500 m^3/day. The ECLWRF is fed by the Hyperion WWTP secondary effluent and accounts with a multi-barrier system (physico-chemical system, UF, RO and UV disinfection), which provides different reclaimed water qualities for aquifer recharge, industrial (Oil & Gas sector) and urban uses (Lazarova et al., 2013). In South-East Asia, The Public Utilities Board (PUB) of Singapore boosted an innovative and referent water management system to guarantee the water supply of the country, including rainfall harvesting, seawater desalination and water reuse. Specifically, the new Tuas WRP will provide through a membrane bioreactor (MBR) followed by RO high quality reclaimed water for local industries and surface water replenishment as Indirect Potable Reuse (IPR) system (Lefebvre, 2018; Tortajada, 2006). In the north of Europe, Dow Water (Dupont) collaborated with a local water utility and the regional water manager of the city of Terneuzen (The Netherlands) to use local wastewater to cover the industrial water needs (30,000 m^3/day) of one of their world's largest chemical-industrial centers (Dow, 2021). Particularly in Spain, AITASA WRP (Tarragona) provides municipal reclaimed water to the petrochemical area (Pintilie et al., 2016), and Arroyo Culebro WRP (Madrid) supplies reclaimed water to a local Pulp & Paper industry.

Nevertheless, main references found in full-scale water reuse systems are associated to extreme water scarcity areas, with a large water demand and thus, a great necessity. With the aim to contribute to expand water reuse, Lee et al. (2020) investigated the drivers and barriers of water reuse, and as mentioned before, there is a need to provide to decision markers key information of which are the capital and operational expenditures (CAPEX and OPEX) of advanced reclamation technologies at different scales, which are the impacts (environmental or economic) and potential savings that can push industrial users to adopt them. Particularly, cost is a key variable in decision making in early stages of technologies implementation to evaluate its financial consistency. This issue takes importance when centralized or decentralized systems are planned, existing significant differences related to economies of scale for both CAPEX and OPEX. These uncertainties are added to the existing governance and economic barriers, holding back private and public investment in water reuse projects.

The aim of this work is to demonstrate the techno-economic reliability of a fit-for-use treatment train to reuse municipal reclaimed water from a Basic Water Reclamation system (BWR) for industrial uses as depicted in Fig. 1. The performance of the different treatment units is assessed in terms of water quality and operation to identify the benefits of two potential pre-treatments for RO membranes. In addition, generic cost curves for the different technologies considered are provided and applied to estimate the CAPEX and OPEX required for scaling at three different industrial sites, e.g., chemical, waste management and electro-coating industries, to meet their different needs.

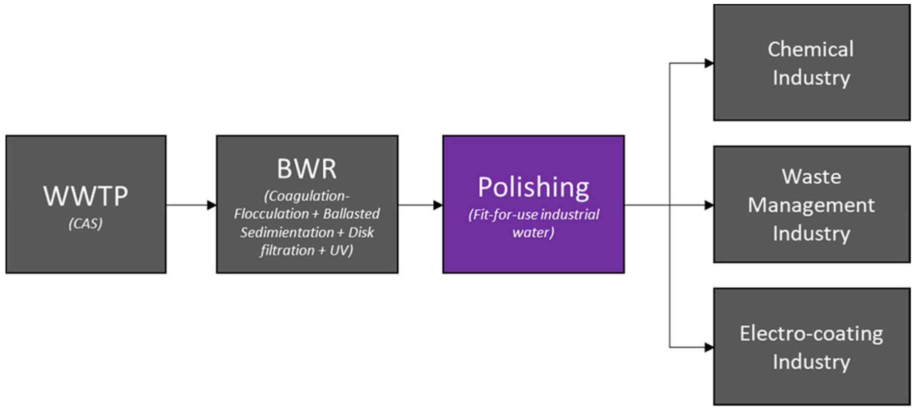

Fig. 1. Overall scheme of the techno-economic analysis for three industries in the fit-for-use treatment train scheme to reuse municipal reclaimed water.

2. Materials and methods

The materials and methods used are described in the following section. From one side the technical assessment methodology is presented, in which the evaluated scenarios are defined, and the prototypes are described, as well as the analytical methods for characterization of water quality. On the other hand, the methods employed for the economic analysis are also described.

2.1. Polishing technologies assessment

2.1.1. Scenarios definition and characterization

Three different target water reuse projects have been evaluated, consisting in different industries from representative market segments (chemical, waste management and electro-coating) interested in reuse municipal reclaimed water to cover their water needs. Valuable information was obtained from different stakeholders who shared their water quality requirements and demands (flow-rates). This characterization was used for the matching between users and tested technologies, and also to scale-up the selected decentralized treatment trains in order to assess them from an economic perspective and to compare the result with the current baseline scenario (current freshwater sources and water polishing systems).

2.1.2. Baseline definition and treatment trains characteristics

El Baix Llobregat WWRP accounts with a conventional activated sludge system followed by a BWR system composed by coagulation-flocculation, ballasted sedimentation, disk filtration and UV disinfection. The total capacity of the water treatment and reclamation plant is 3.25 m^3/s. A treatment train with different water reclamation technologies was operated at pilot scale for a total of 18 months in El Baix Llobregat WWRP (Barcelona, Spain) to assess from a techno-economic point of view two different treatment trains and scale them up at different levels based on the user's requirements.

The treatment train consisted of two lines in parallel: i) a polymeric hollow fiber inside-out UF of 3.5 m^3/h and ii) a high-performance adsorbent column of 2.2 m^3/h. Both lines fed a two-stage RO plant with 1.5 m^3/h of capacity. Each one of the units had sampling points to validate the water qualities obtained and validate its reuse for industrial uses. The prototype was fully automatized and operational data (pressure and flow) were acquired from the SCADA system to guarantee the monitoring of the different unit's performance. The prototype scheme is shown in Fig. 2.

The ultrafiltration unit consisted in a single module of polymeric hollow fiber membranes (AQUAFLEX 64, PENTAIR) with a total membrane area of 64 m^2 operated in dead-end mode. The technical characteristics are summarized in Table SM 1. The feed water was pumped and circulated through the membrane fibers in an inside-out filtration, collecting the produced permeate in the module shell. Hydraulic cleanings were performed consisting in a combination of a backwash (15 m^3/h for 30 s) and the circulation of raw water in the feed side (4 m^3/h for 30 s) to remove the cake layer and the organic matter accumulated in the module during filtration cycles. Additionally, chemical enhanced backwashes (CEB) were also applied periodically in acid (1.4 g/L of HCl (15%)) and alkaline conditions (0.2 g/L of NaOCl (15%) and 1.4 g/L of NaOH (50%)) to recover permeability. The characteristics of the reagents used are summarized in Table SM 2.

On the other hand, the adsorbent column accounted with a load of 115 kg of a high-performance material. This material was an innovative carbon-based nanostructured material (CNM) from Blücher (SARATECH®), which technical characteristics (provided by the manufacturer) are summarized in Table SM 3. The filter was operated with a filtration velocity between 8.5 and 10 m/s and allowed the possibility to perform controlled backwashes (BW) several times per day, at a fixed flow of 4 m^3/h.

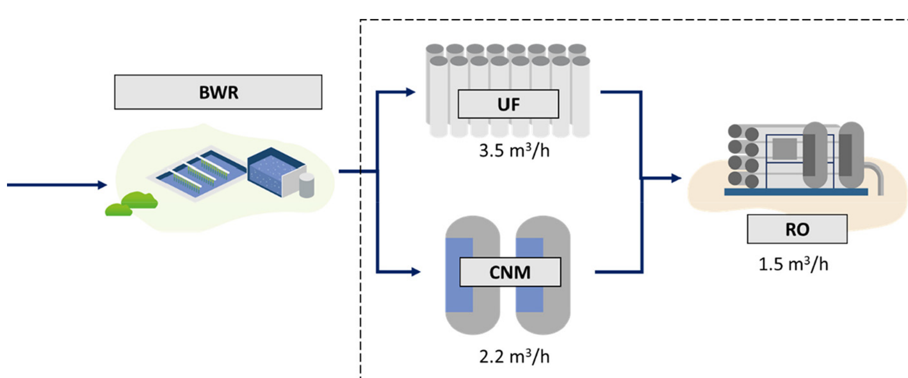

Fig. 2. Experimental pilot scheme of two different RO pre-treatment: a) incorporating an UF membrane stage and b) a carbon-based nanostructured material (CNM). The feed is treated municipal wastewater using a Basic Water Reclamation scheme.

Finally, the two-stage RO unit was designed to be operated with a permeate production of 1.5 m^3/h at a fixed recovery of 70%. It consists of two pressure vessels and the first and second stage contained 4 and 2 membrane elements (Hydranautics LFC3-LD-4040), respectively. The technical characteristics are included in Table SM 4. The high-pressure pump accounted with a speed driver to adjust pressure and flow to a fixed set point, and the rejection valve was manually controlled.

2.1.3. Analytical methods

In order to have a complete characterization of the different generated effluents, samples were taken weekly. Regarding physico-chemical parameters, pH and conductivity were measured online (Mettler Toledo, INPRO 4260/SG/120). Turbidity was measured through a turbidimeter Hach Lange 2100, and SS were analysed using standard methods 2540 (APHA, 1995). COD was analysed using test kits (Hatch Lange LCI test) and TOC was measured with a Shimadzu VSH-TOC analyser. Sodium, Calcium and Copper were measured through ICP/MS (Pekin-Elmer Nexion 300×).

Total aerobic colonies were counted on a nutrient agar culture medium after 48 h of inoculation at 36 °C (UNE-EN-ISO 6222:1999). *E. coli* was measured through Colilert kits (Minimal Media ONPG-MUG Test) and *Legionella* was measured through enzyme immunoassay (Kazandjian et al., 2021). Finally, the presence or absence of *Nematode eggs* was determined through Bailenger method (WHO, 1989).

Additionally, seven OMP (three pesticides from the triazines family and four Polycyclic Aromatic Hydrocarbon (PAH) compounds) were selected (Table SM 5) and analysed through C18-Solid phase extraction Gas Chromatography-Triple Quadrupole Mass Spectrometry (7000 GC/MS/MS Agilent Technologies).

Three samples of the CNM were analysed to characterize their porous textural properties such as surface area, micropores volume, outer surface, and porosity distribution. Characterization was done through the determination of adsorption and desorption isotherms of N_2 (−196 °C) and adsorption of CO_2 (0 °C) using a volumetric adsorption equipment (Autosorb 6 y 6B, Quantachrome).

Finally, Silt Density Index (SDI) was measured in both UF and CNM effluents using standard methods ASTM D4189-07 in order to identify how suitable is to feed the RO membrane.

2.2. Economic assessment

Historically, the calculation of CAPEX in wastewater reclamation plants and distribution networks has been based on a detailed engineering project assessment, being considered specific aspects such as sizing and selection of commercial equipment, construction materials and instrumentation, and the evaluation of site adaptation requirements (Raj Sharma, 2010). The preparation of these assessments is time consuming and requires the implication of experts from technologies providers.

In this study, analysis was based on Williams Law, in which cost functions follow an exponential trend, $C = \beta \cdot Q^{\alpha}$, in which C is cost, Q is capacity and β and α are constants (Guo et al., 2014). This approach considers the economy of scale, being applicable for both capital and O&M expenditures. Tribe and Alpine (1986) explained that the scale coefficient (α) ranges between 0.5 and 1 and represents the scalability factor, which may vary depending on the technology nature, being $\alpha = 0.6$ in many cases the best adjustment in cost curves. Nevertheless, it has been observed and reported that not all technologies scale-up following the “0.6 rule”.

On the other hand, OPEX (expressed as €/m^3 of produced water) is not a constant value associated to each technology and presents a range of variation related to scale economies. It depends on energy consumption; beyond depending on water quality and operational conditions applied, pumping efficiency varies significantly regarding capacity, as well as the indirect energy costs associated to the installed power of building and control room. Additionally, based on the volumes of chemical reagents purchased and distribution logistics, the associated market price changes.

During the eighties, to boost a rapid decision making, the US Environmental Protection Agency (USEPA) developed cost curves based on actual and conceptual designs of different capacities (USEPA, 1979). Several authors, in recent decades, have applied this method and developed corresponding cost equations based on regression lines, which can also be integrated in computer programs in order to interpolate a CAPEX or OPEX value regarding the required capacity (Raj Sharma, 2010). The accuracy in the estimation of costs, both CAPEX and OPEX, depends on how key variables and assumptions are defined. Regarding CAPEX estimation, the following items have been considered: i) Site work or site preparation, ii) Equipment & housing, iii) Electrical & Instrumentation. On the other hand, the following variables are considered for OPEX estimation: i) Energy consumption, ii) Chemicals consumption, iii) Equipment replacement and maintenance, iv) Waste and By-products management.

Different quotations have been identified and compiled to calculate CAPEX and OPEX curves, which were extrapolated for the different treatment capacities defined by the end-users (1890, 215 and 100 m^3/day for chemical, waste management and electro-coating industries, respectively). In all quotations, the Consumer Price Index (CPI) has been updated to 2021. On the other hand, detailed engineering, manpower and contingency plan have been excluded to ease the comparison among quotations compiled. This also answers to the worldwide variability in salary ranges for workers and engineers.

3. Results and discussion

In the following section the results obtained are described and discussed. Firstly, a water quality evaluation (Section 1) is presented, considering both physico-chemical parameters and OMP removal. Secondly, the prototype performance results (Section 2) are described, in which UF and CNM are evaluated, together with the RO. Finally, in Section 3, CAPEX and OPEX cost curves are used to estimate the full-scale cost of the defined industrial water reuse projects and assess them from a techno-economic perspective.

3.1. Water quality assessment

The different effluents produced by the prototypes were assessed in terms of water quality with the aim to compare them with the regulations considered and the end-users requirements. Conventional physico-chemical parameters and selected OMP were analysed, and removal efficiencies were estimated.

3.1.1. Evaluation of conventional physico-chemical stages of pollution load removal

The characterization of the basic reclaimed water influent and the effluents from the different process units of the prototype are summarized in Tables SM 6 and SM 7. The current basic reclamation scheme of El Baix Llobregat was designed for the removal of suspended solids, turbidity, organic matter, and microbiological indicators. Its mean turbidity and SS values were 0.7 ± 0.2 NTU and 2.5 ± 1.0 mg/L, respectively. Additionally, in terms of COD and TOC, mean concentrations of 23 ± 4 mg O_2/L and 8 ± 1 mg C/L were measured. Nevertheless, the treatment units integrating the BWR do not account with desalination steps and as it will be depicted in Section 3.3.2, despite that it is not considered in the Spanish regulation for water reuse (RD1620/2007), the target industrial end-users requirements demand the removal of salinity measured as electrical conductivity and the total reduction of hardness. In this sense, the application of a post-treatment based on desalination (RO) to achieve these objectives is required, together with the proper pre-treatments (CNM or UF) to guarantee the correct performance and lifespan of RO membranes.

The BWR effluent presented average conductivity of 2090 ± 94 μS/cm and total hardness was 454 ± 39 mg $CaCO_3$/L. Main measured cations were sodium and calcium, which mean concentrations were 255 ± 30 mg/L and 119 ± 11 mg/L, respectively. In addition, main measured anions were chlorides, sulfates and bicarbonates, which mean concentrations were 388 ± 53 mg/L, 181 ± 97 mg/L and 331 ± 28 mg/L, respectively.

Finally, due to the disinfection step through UV and chlorination, the microbiological indicators were below the limit of detection.

Regarding the CNM filter and UF, the main objective was to remove dissolved organic matter. An average removal efficiency of 30% of COD and 32% of TOC was measured for CNM. On the other hand, the removal efficiency found in UF was 21% and 15% for COD and TOC, respectively.

Finally, the RO step allowed a reduction of conductivity from 2090 ± 94 μS/cm to 25 ± 6 μS/cm, which was one of the main objectives of this treatment step. Sulfate concentrations were reduced below the detection limit, as well as bicarbonates and calcium, which represented a total removal of hardness (>99%). Sodium and calcium were reduced to 4.8 ± 1.0 and 4.7 ± 2.0, respectively.

3.1.2. Evaluation of OMP removal

Average removal efficiencies for triazine pesticides and PAH analysed are collected for the different process units in Table 1.

CNM allowed high removal efficiencies for triazine pesticides, in which terbuthylazine presented removal efficiencies of 67% and atrazine of 97%. Similar results were found by Borrull et al. (2021) who reported efficiencies of total triazines between 95.3% and 68.0% at the outlet of a GAC filter in a DWTP when inlet concentrations were above 10 ng/L. Regarding PAH, moderate efficiencies were found for anthracene and fluorene (46% and 27%, respectively), while in the case of pyrene and naphthalene low efficiencies were achieved (5% and 3%, respectively). Scarce data have been found for the CNM adsorbents and only a similar material as Lewatit® AF 5 reported it is used for adsorptive polishing in water treatment applications for traces of organic substances such as chlorinated hydrocarbons, MTBE, organic phosphates, amines, pesticides, herbicides, and metabolites (Reczek et al., 2020).

UF presented low efficiencies (<15%) for the different OMP analysed. This is associated to the molecular weight cut off (MWCO) of UF membranes, in which those OMP with higher molecular weight (MW) than 3 kDa can easily pass through the membrane. Similar behaviour in pharmaceutical compounds in UF membranes was reported by Echevarría et al. (2020). On the other hand, atrazine presented moderate removal efficiency (25%) which, as suggested by López-Fernández et al. (2016), might be associated to its relatively high lipophilicity (log Kow > 2.5) and the potential sorption to the membrane layer, composed by poly-vinyl difluoride (PVDF) or onto the cake layer formed along the filtration stages.

In the case of RO, very high removal efficiencies (>95%) were found for triazine pesticides. Nevertheless, limited efficiencies between 20% and 35% were found for PAH. Argun et al. (2020) indicated that the main removal mechanism of PAH with low molecular weight and high volatility such as naphthalene and anthracene is stripping when investigated strategies for the removal of organic compounds from leachates; thus, these compounds present high removal efficiencies in bioreactors. On the other hand, their low MW difficult their removal in dense membranes such as RO or NF.

Table 1
OMP concentration (ng/L) and removal efficiencies (%) along the different WWTT treatment stages (BWR, CNM, UF and RO).

OMP	BWR effluent	CNM permeate	UF permeate	RO permeate
Number of samples	10	5	5	10
Terbuthylazine	15 ± 7	6 ± 1 (67% ± 25%)	14 ± 1 (5% ± 5%)	1 ± 1 (98% ± 5%)
Atrazine	26 ± 4	1 ± 1 (97% ± 10%)	19.5 ± 1 (25% ± 5%)	1 ± 1 (96% ± 1%)
Anthracene	8 ± 5	5.1 ± 1 (46% ± 25%)	4.6 ± 1 (8% ± 6%)	5.3 ± 1 (33% ± 25%)
Fluorene	6 ± 4	4.6 ± 1 (27% ± 20%)	5 ± 1 (7% ± 6%)	4.2 ± 1 (32% ± 13%)
Pyrene	7 ± 4	6 ± 1 (5% ± 2%)	6 ± 1 (10% ± 8%)	5 ± 1 (23% ± 12%)
Naphthalene	6 ± 2	6 ± 1 (3% ± 1%)	6 ± 1 (5% ± 5%)	5 ± 1 (30% ± 15%)

3.2. Pilot treatment train performance

3.2.1. Ultrafiltration stage

The optimization of the UF system was based on maximize the production and reduce the main operational expenditures. Different steps were followed to achieve this objective, considering as main variables the water yield and production rate. Water yield (WY) was calculated as the net production volume over the total filtered volume, and production rate (PR) was calculated as the amount of time in which the membrane was in filtration mode over the total operational time.

Fouling velocity, expressed as permeability decline (PD) over time (dK/dt) and measured as the slope of the liner regression of permeability in five chemical cycles, was calculated for each operational condition set. A maximum PD of 10 LMH/bar/day was established based on membrane design recommendations to define whether the operational conditions applied were sustainable in terms of fouling or not. After each step, an intensive chemical cleaning was applied to recover permeability to baseline conditions. The different steps followed, and the results obtained in terms of WY (%) and PR (%) are plotted in Fig. 3.

Firstly, filtration flux was gradually increased from 31 to 62 LMH, applying a fixed filtration time of 30 min and thus performing two hydraulic cleanings per hour, as it can be seen in Fig. SM 1. Additionally, one CEB was applied every 10 h. As result, WY increased from 72% to 84% while PR was kept in 79%, since it is associated to operational time and not produced volume. Fouling slopes suggested that applying 62 LMH there was PD of 18 LMH/bar/day, representing a risk on the integrity of the membranes. Thus, 55 LMH was selected as the most suitable flux, allowing to increase water yield to 84%.

In a second step, fixing 55 LMH as the optimal flux, filtration time was varied from 20 to 60 min. Based on the fouling slopes obtained, to keep 30 min as filtration seem to be the best option as it can be seen in Fig. SM 2. Moreover, a trial to reduce the hydraulic cleaning duration from 60 to 30 s was done, obtaining promising results in terms of fouling and implying a WY of 91% and a PR of 80%.

Finally, in a third step, chemical cleanings frequency was varied from 5 to 24 h^{-1}. In this case, as it is depicted in Fig. SM 3, results clearly indicated that 10 h^{-1} was the most suitable option, considering that higher frequencies leaded to not completely recover permeability and the risk of accumulated fouling. Additionally, different soaking times were applied (60, 30 and 15 min) in order to increase production time. No significant variances were found in permeability recovery by applying the soaking time of 15 min, thus it resulted the optimal option, implying an increase of PR to 91%.

Based on these results, the operational conditions selected as the optimal to apply them in a long-term membrane performance test consist of a filtration flux of 55 LMH (which corresponds to a net production of 3.5 m^3/h), applying a filtration time of 30 min and performing CEBs every 10 h (and 15 min of soaking per cleaning type).

Once the optimal operating conditions were obtained, long term membrane performance was evaluated operating the UF module under optimal conditions for 270 h. During this period, permeability remained stable between 200 and 100 LMH/bar (Fig. 4).

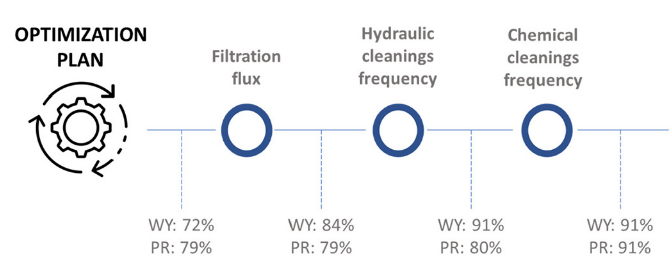

Fig. 3. Details of the optimization plan of the ultrafiltration stage including the WY (%) and PR (%) along the filtration operation cycles including the hydraulic and chemical cleanings frequencies.

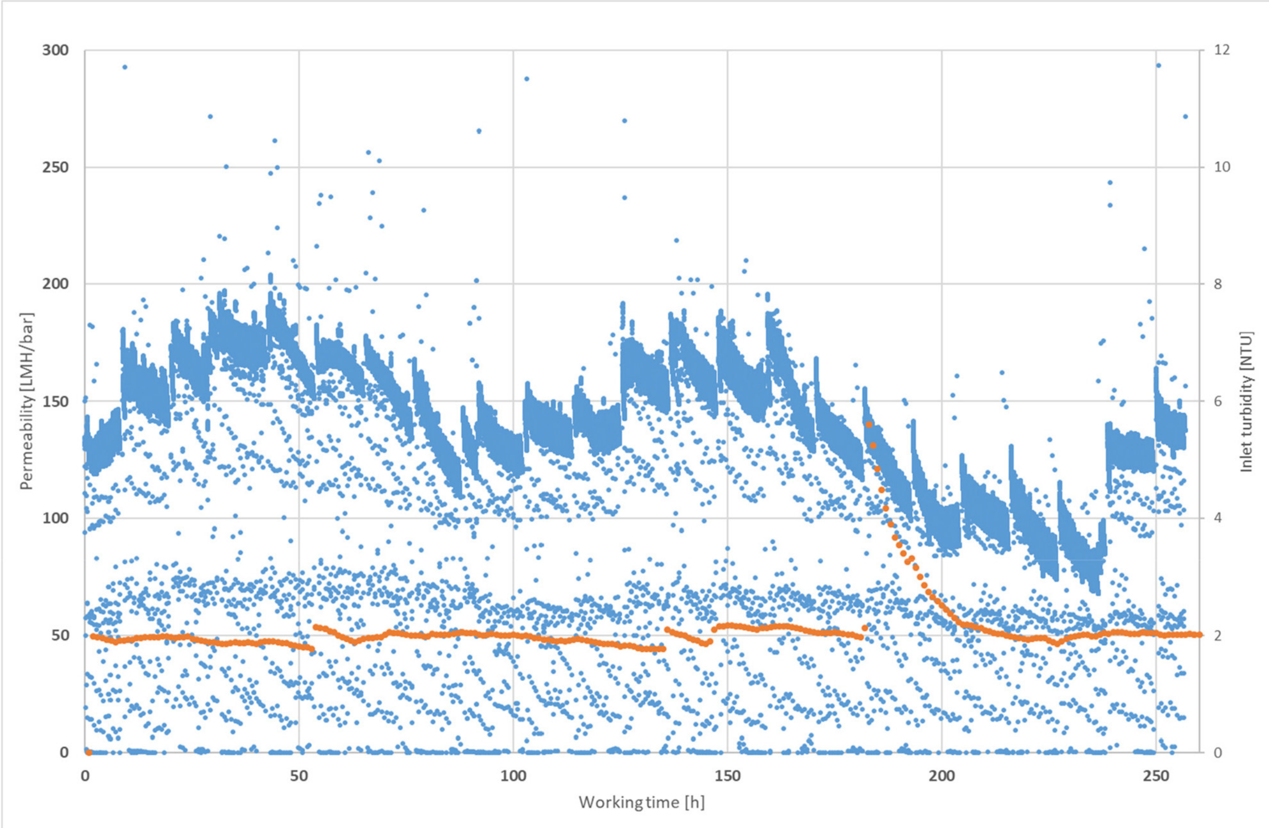

Fig. 4. Long-term UF Permeability (blue) and turbidity (orange) evolution.

After 180 h of operation, it was detected a fouling event in which permeability reached lower values than 100 LMH/bar. This decline was clearly correlated to an excess of turbidity associated to a rainfall event that compromised the performance of the basic reclamation system and thus the inlet water quality in the UF.

3.2.2. CNM adsorption stage

The CNM filter was operated at a filtration velocity between 8.5 and 10 m/h (1.7–2.2 m^3/h) for approximately 25,000 bed volumes. Hydraulic cleanings consisting in a backwash (BW) were performed when pressure drop, measured as the difference between the inlet and outlet pressure, reached 1.5 bar.

During this period, COD, TOC and absorbance at 254 nm were monitored in the inlet and outlet of the filter, in order to calculate C/C_0 curve and decide when regeneration was required. These three parameters were selected as surrogates of the organic to evaluate the removal of organic matter as they were easily monitored. As it can be seen in Fig. 5, under the flowrate conditions, at the initial stages <1000 BV, a removal of 90, 85 and 80% of COD, TOC and absorbance 254 nm were obtained, respectively for the first samples. Nevertheless, as the filtration time increases (e.g., after 8000 BV) the removal efficiency decreased approximately to 25, 30 and 40%, respectively.

Results found in this research were compared with those reported by Mailler et al. (2016), who assessed conventional GAC in municipal wastewater. COD, TOC and UV 254 removal efficiencies of 21–48%, 13–44% and 22–48%, respectively were reported for GAC. On the other hand, in this study, CNM allowed a removal efficiency for COD, TOC and UV 254 nm of 75–10%, 76–20%, 90–19%, respectively.

Once C/C_0 reached 0.8 for COD and TOC, the filter still operated stable and was able to feed RO; nevertheless, in order to reach more detail on the technical performance of this innovative material, CNM was regenerated by the manufacturer. According to literature a similar microporous carbonaceous sorbent as Lewatit® AF 5 regeneration could be achieved using steam or hot water or other organic solvents as the separation mechanism is partially via low energy hydrogen bonding (Kaleh and Geißen, 2016; Reczek et al., 2020) After its regeneration, the adsorbent was characterized, and results are listed in Table SM 8.

Both virgin and regenerated samples presented similar textural properties, which indicates that the regeneration was effective. On the other hand, as expected, the saturated sample showed a significant lower surface area BET and micropores volume.

Fig. 6 shows the distribution of the pore size of the analysed samples. Most probable size ranges between 0.7 and 1 nm in all samples with a second size of wide micropores with a pore size around 1.6 nm (Fig. 6A). A small contribution of mesopores (Fig. 6B) between 5 and 30 nm was found also for the three samples. The results obtained suggest that the

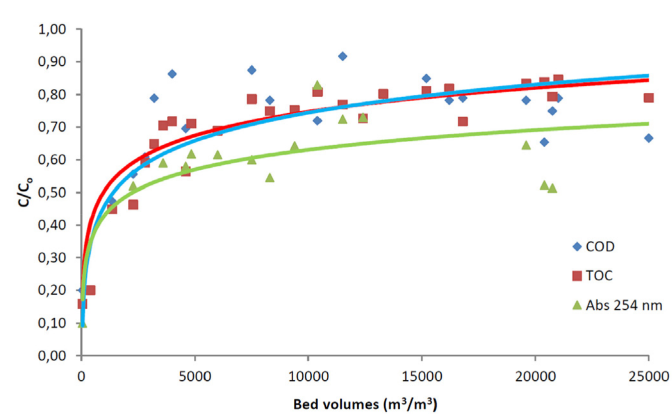

Fig. 5. Variation of the COD, TOC and Absorbance values at 254, expressed as (C/C_o) for the sorption stage using Carbon Nanostructured Material (CNM).

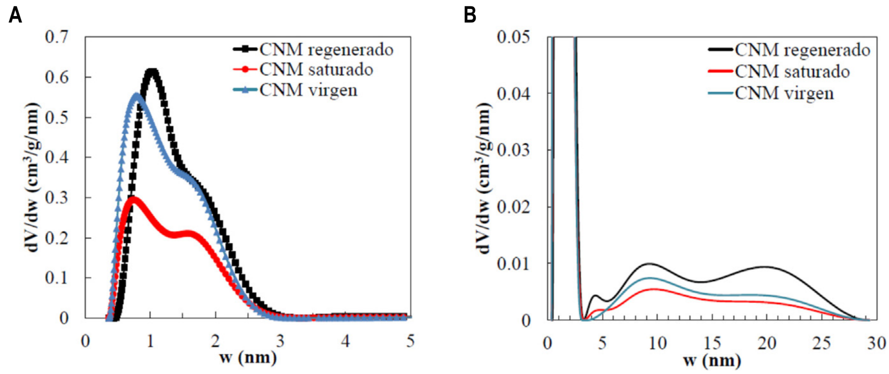

Fig. 6. Pore size distribution of the micropore (A) and mesopore (B) regions.

saturation is mainly associated to the filling of micropores. Once the regeneration is done, the surface area for adsorption is recovered (1720 m^2/g), with a slightly increase of its mesoporosity (from 0.10 to 0.13 cm^3/g) and outer area (from 75 to 100 m^2/g). Additionally, a slight widening of the microporosity was observed.

3.2.3. Reverse osmosis stage

The RO prototype was operated fixing a recovery of 70% for approximately 500 h. During the first 250 h it was fed with the CNM permeate (phase 1), while the rest of the period was fed with the UF permeate (phase 2) as shown in Fig. 7.

Despite COD and TOC values were slightly lower in CNM permeate (Table SM 6), the average SDI found after 10 samples was 4.0 ± 0.5, while in UF permeate mean SDI was 2.0 ± 0.5. As it can be seen in Fig. 7, during the first phase TC Permeability declined from mean values of 37 LMH/bar to 35 LMH/bar. Moreover, when the RO prototype was fed with UF permeate, the TC permeability remained stable, even was slightly improved.

Recently Cai et al. (2021) evaluated two different pre-treatments (biofiltration, coagulation and microfiber filtration (BCMF) vs. UF) to reduce fouling in RO. The results showed that UF pre-treatment process allowed a more controlled permeability evolution and it was correlated with a lower modified fouling index ($MFI_{0.45}$). Similar results were found by Benito-Alcázar et al. (2010), who investigated different pre-treatments (GAC and UF) for RO applied for industrial water reclamation in the petrochemical sector. In their work, TOC, COD, turbidity and SDI_{15}, were used to determine the better pre-treatment in terms of fouling mitigation in the RO membranes. Due to a lower SDI, UF was also postulated as better pre-treatment than GAC despite presenting higher TOC and COD values.

3.3. Techno-economic assessment

In this section the techno-economic assessment is described. In Section 3.3.1, cost curves for UF, adsorbent filters and RO are calculated. These curves are used in Section 3.3.2 for estimating CAPEX and OPEX for the scenarios defined in Section 3.3.3, allowing to estimate the potential savings or over costs associated to potential water reuse projects for industrial water supply.

3.3.1. Cost curves calculation

Cost curves were calculated (Table 2) for the different reclamation technologies evaluated. As it has been explained, different quotations were obtained from different engineering firms to estimate CAPEX. On the other hand, data from industrial O&M contracts was obtained to estimate OPEX. Raw data to calculate the curves has been included in the supplementary material section (Tables SM 9 and SM 10).

Firstly, regarding UF, 8 and 13 quotations were used to calculate CAPEX and OPEX cost curves, respectively (Figs. SM 4 and SM 5). These correspond to ultrafiltration plants which capacity ranged from 80 to 2800 m^3/day. Considered UF plants are based on side stream pressurized filtration modules (both hollow fiber or tubular) operating in dead-end configuration and the maximum turbidity allowed is 20 NTU. Based on the obtained results and considering mentioned capacity range, UF CAPEX and OPEX might vary between 1150 and 255 €/m^3/day and 0.59 and 0.21 €/m^3, respectively. Iglesias et al. (2017) reported a CAPEX range between 312 and 158 €/m^3/day for UF plants in municipal water plants with capacities ranging from 1000 to 25,000 m^3/day, which are consistent with the results obtained in this study.

Secondly, quotations for adsorbent columns with capacities ranging from 95 to 3000 m^3/day were collected. Due to the lack of available data,

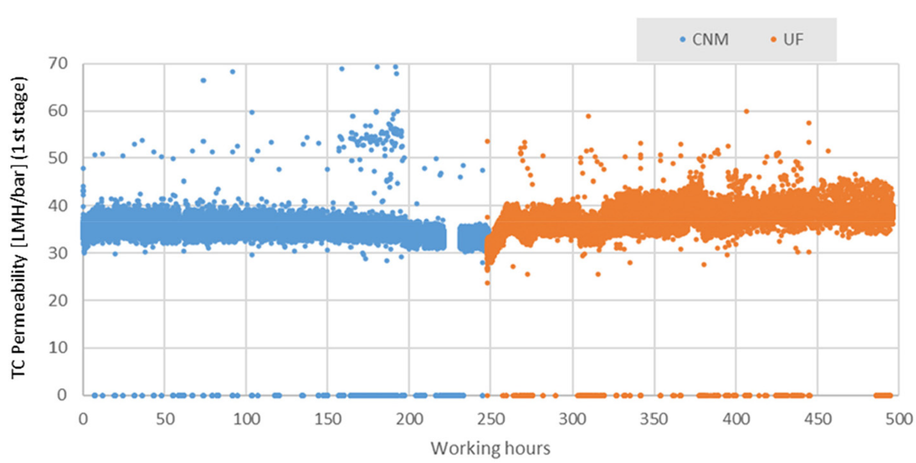

Fig. 7. Long-term RO permeability evolution regarding feed water (UF or CNM).

Table 2
CAPEX and OPEX cost curve equations for evaluated reclamation technologies.

Treatment unit	CAPEX cost curve			OPEX cost curve		
	Number of quotations	Equation	R^2	Number of quotations	Equation	R^2
UF	8	$CAPEX = 4268 \cdot x^{-0.34}$	0.899	13	$OPEX = 2.06 \cdot x^{-0.30}$	0.875
Adsorbent column (GAC)	10	$CAPEX = 8250 \cdot x^{-0.59}$	0.897	7	$OPEX = 0.13 \cdot x^{-0.03}$	0.813
RO	29	$CAPEX = 3275 \cdot x^{-0.46}$	0.954	10	$OPEX = 7.92 \cdot x^{-0.38}$	0.868

these quotations include both drinking water and water reclamation applications and only those plants operating at a filtration velocity between 10 and 15 m/h were considered. Additionally, these results correspond to conventional commercial products, which price ranges between 3 and 4 €/kg of adsorbent, including transport, commissioning, and disposal. Obtained results indicated that CAPEX and OPEX might vary between 445 and 55 €/m^3/day and 0.13 and 0.11 €/m^3, respectively. Similar results were obtained by Plumlee et al. (2014), who provided also OPEX cost curves for biological activated carbon (BAC) filters ranging from 0.15 to 0.10 €/m^3. On the other hand, when advanced adsorbents such as CNM are used, the impact on OPEX needs to be considered due to its significantly higher price (50 €/kg of adsorbent). In this case, OPEX might vary from 1.03 and 1.01 €/m^3, considering that adsorbent purchase and regeneration costs represent more than 95% of OPEX.

Finally, for RO, quotations of water reclamation plants presenting recoveries between 50 and 75% and capacities between 28 and 2760 m^3/day were used. In this case, CAPEX and OPEX varied from 675 to 91 €/m^3/day and 5.92 to 0.49 €/m^3.

3.3.2. Water fit-for-use strategy definition

With the aim to size the treatment scheme for the defined scenarios, the three industrial sites (Fig. SM 6) were evaluated in terms of non-potable water quality requirements and demands (Table 3). Additionally, based on Tables SM 6 and SM 7 results, it has been indicated if

Table 3
Industrial water quality requirements regarding market segment and Spanish Royal Decree regulation.[a]

Industrial market segment/effluent	Industrial uses	Flow [m^3/day]	pH [–]	Conductivity [μS/cm]	Chloride [mg/L]	Total hardness (mg $CaCO_3$/L)	Turbidity [NTU]	SS [mg/L]	COD [mg O_2/L]	TOC [mg C/L]	UF	CNM	UF + RO	CNM + RO
Chemical	Process water (reactors)	1500	6.0–7.5	<250.0	<65.0	15.0	–	–	<4.0	<1.2	N	N	Y	Y
	Cleaning operations (Stainless steel equipment)	130	6.0–7.5	<250.0	<65.0	15.0	–	–	<4.0	<1.2	N	N	Y	Y
	Cleaning operations (pavements)	100	6.0–7.5	<4000.0	<1200.0	–	–	–	–	–	Y	Y	Y	Y
	Cooling towers supply	160	6.0–8.0	<250.0	<65.0	15.0	–	–	<4.0	<1.2	N	N	Y	Y
Waste management	Cooling towers	50	6.5–9.0	<700.0	–	–	<15.0	–	–	–	N	N	Y	Y
	Reagents preparation	25	7.0–9.0	<700.0	–	–	<1.0	–	–	–	N	N	Y	Y
	Boiler feed	140	>7.0	<700.0	–	<1.0		–	–	–	N	N	Y	Y
Electro-coating	Process water (coating baths)	100	6.5–9.5	<250.0	<250.0	<1.0	<1.0	–	<5.0	–	N	N	Y	Y
Spanish RD 1620/2007 (municipal wastewater reuse)	Process and cleanings	N/A	N/A	N/A	N/A	N/A	10	35	N/A	N/A	Y	Y	Y	Y
	Cooling towers	N/A	N/A	N/A	N/A	N/A	1	5	N/A	N/A	Y	Y	Y	Y

[a] Y: Meet the quality requirements; N: Do not meet the quality requirements.

the evaluated technologies meet the water quality requirements or not. A water yield of 90 and 99% has been considered for both UF and CNM (or GAC) pre-treatments and a recovery of 70% has been estimated for RO.

As it is indicated in Table 3, the chemical industry presented a process water demand of 1500 m^3/day, which required a conductivity below 250 μS/cm, chloride levels below 60 mg/L and a total hardness of 15 mg $CaCO_3$/L. Additionally, COD and TOC maximum levels were 4 mg O_2/L and 1.2 mg C/L. The same requirements were stablished for cleaning operations for stainless steel equipment (130 m^3/day) and cooling towers supply (160 m^3/day). Thus, to meet this water quality and cover these demands, quality of RO permeate was required. On the other hand, the cleaning operations for pavements (100 m^3/day) presented lower quality requirements, with a maximum conductivity and chloride concentration of 4000 μS/cm and 1200 mg/L, respectively, which could be met with treated water with UF or CNM. Two different lines (UF + RO and CNM + RO) have been projected and are described in Fig. SM 6, in which net production capacities of 2657 m^3 of UF or CNM permeate/day and 1790 m^3 of RO permeate/day are needed.

In the waste management industry, the main water consumption was for boiler feed (140 m^3/day), in which lower conductivity and total hardness values lower than 700 μS/cm and 1 mg $CaCO_3$/L were required. Additionally, the industrial site had a daily consumption for cooling towers and reagents consumption of 50 and 25 m^3/day, respectively, and had the same requirements for conductivity, apart from a limitation on turbidity. The possibility to blend both UF and RO permeates in a buffer tank to achieve the reduction of conductivity (but minimize the RO capacity) was excluded under request of the site, since it implied a higher control in order to minimize potential microbiological risk. Thus, the whole demand (215 m^3/day) needs to be covered with RO permeate, which requires UF/CNM net permeate capacity of 307 m^3/day.

Finally, the electro-coating industry, requested 100 m^3/day of process water supply, which requirements were lower conductivity than 250 μS/cm, lower chloride and total hardness concentrations than 250 mg/L and 1 mg $CaCO_3$/L, respectively, and COD and turbidity values below 5 mg O_2/L and 1 NTU, respectively. Based on the water quality, 100 m^3/day of RO permeate are needed, which needs from 143 m^3/day of UF/CNM net permeate.

The water quality requirements provided by the industrial users are significantly more restrictive than the Spanish regulation (Royal Decree 1620/2007) for water reuse in industrial applications. The RD 1620/2007 limits the SS and turbidity concentration and microbiological activity but does not limit salinity, hardness, or chloride, which as it has been seen, are of major concern for industrial key players.

3.3.3. Economic evaluation

The economic evaluation for the different industrial sites is described in Table 4. The current water source and demand of the industrial users is indicated, as well as its associated water cost. Moreover, the CAPEX and OPEX of the alternative decentralized schemes (UF + RO and GAC + RO) fed by municipal reclaimed water are depicted to estimate a total cost and potential savings.

These values have been calculated using the cost curves equations developed in this study and considering a depreciation for the electromechanical equipment of 10 years. A reclaimed water tariff of 1.26 €/m^3 has been used as mean indicative value suggested in a technical study (LEITAT, 2008) supported by the Catalan Water Agency, which is one of the main regulatory bodies in the territory.

The chemical industry covers its current water demand (1890 m^3/day) by applying a RO treatment on well-extracted water. Due to the relatively low costs of well exploitation in this area (compared with tap water supply), their water cost was 1.05 €/m^3. On the other hand, to use reclaimed water as an alternative requires an investment of 963.7 k€ for UF + RO and 396.1 k€ for GAC + RO. Additionally, considering both reclaimed water tariff and the exploitation cost (CAPEX + OPEX) of the polishing system, a total cost of 2.02 €/m^3 and 1.87 €/m^3, respectively, is estimated. These costs are higher than the current one, thus instead of savings, to apply this reuse project would imply and additional economic cost for the industry.

In the case of the waste management industry, its current water demand (215 m^3/day) is covered with tap water followed by an ion-exchange (IEX) stage for softening, which has a total cost of 2.95 €/m^3. In this case, CAPEX was estimated in 219.9 k€ for the UF + RO and 146.7 k€ for the GAC + RO, and considering all exploitation costs and reclaimed water tariff, a total cost of 2.82 €/m^3 and 2.43 €/m^3 was estimated, which represent savings of 0.13 €/m^3 and 0.52 €/m^3, respectively.

Finally, the electro-coating industry covers its demand for process water (100 m^3/day) with tap water followed by RO, and accounts with a current cost of 3.80 €/m^3. CAPEX of 136.9 k€ and 102.2 k€ have been estimated for UF + RO and GAC + RO, respectively, with a total cost of 3.31 €/m^3 and 2.82 €/m^3, which represent savings of 0.49 €/m^3 and 0.98 €/m^3, respectively.

4. Discussion

The novelty of the present study relies in the validation of a pilot-scale water reclamation scheme and the techno-economic assessment of decentralized water reuse systems to promote the use of municipal reclaimed water in the industrial sector. The two potential schemes (UF + RO and CNM + RO) are assessed from an operational perspective and a deep revision of economic data has been done to calculate generic

Table 4
Economic evaluation for decentralized water reuse projects in the three industrial sites.

	Chemical industry		Waste management industry		Electro-coating industry	
Current water source	Well + RO		Tap water + IEX		Tap water + RO	
Total water consumption for defined industrial uses	1890 m^3/day		215 m^3/day		100 m^3/day	
Current water cost	1.05 €/m^3		2.95 €/m^3		3.80 €/m^3	
Alternative water sources	UF + RO	GAC + RO	UF + RO	GAC + RO	UF + RO	GAC + RO
UF/CNM capacity	2657 m^3/day	2657 m^3/day	307 m^3/day	307 m^3/day	143 m^3/day	143 m^3/day
RO capacity	1790 m^3/day	1790 m^3/day	215 m^3/day	215 m^3/day	100 m^3/day	100 m^3/day
Total CAPEX	963,786 €	396,110 €	219,941 €	146,757 €	136,934 €	102,270 €
UF/GAC	776,824 €	209,148 €	147,786 €	74,603 €	89,171 €	54,507 €
RO	186,961 €	186,961 €	72,155 €	72,155 €	47,763 €	47,763 €
Depreciation UF/GAC	0.08 €/m^3	0.02 €/m^3	0.19 €/m^3	0.10 €/m^3	0.24 €/m^3	0.15 €/m^3
Depreciation RO	0.03 €/m^3	0.03 €/m^3	0.06 €/m^3	0.06 €/m^3	0.09 €/m^3	0.09 €/m^3
Total OPEX	0.65 €/m^3	0.56 €/m^3	1.31 €/m^3	1.01 €/m^3	1.72 €/m^3	1.31 €/m^3
UF/GAC	0.19 €/m^3	0.10 €/m^3	0.41 €/m^3	0.11 €/m^3	0.52 €/m^3	0.11 €/m^3
RO	0.46 €/m^3	0.46 €/m^3	0.90 €/m^3	0.90 €/m^3	1.20 €/m^3	1.20 €/m^3
CAPEX + OPEX	0.76 €/m^3	0.61 €/m^3	1.56 €/m^3	1.17 €/m^3	2.05 €/m^3	1.56 €/m^3
Reclaimed water tariff[a]	1.26 €/m^3	1.26 €/m^3	1.26 €/m^3	1.26 €/m^3	1.26 €/m^3	1.26 €/m^3
Total cost	2.02 €/m^3	1.87 €/m^3	2.82 €/m^3	2.43 €/m^3	3.31 €/m^3	2.82 €/m^3
Savings	−0.97 €/m^3	−0.82 €/m^3	+0.13 €/m^3	+0.52 €/m^3	+0.49 €/m^3	+0.98 €/m^3

[a] The reclaimed water tariff considered is an indicative value based on other references. An actual tariff has not been estimated in the demonstrated case study.

cost curves for CAPEX and OPEX of the evaluated technologies, allowing the cost assessment in three industrial sites and providing relevant results to support decision making for new water reuse projects. A literature revision of similar published works has been done.

The technical feasibility and economic costs of several reclamation technologies has been reported by different authors, with special mention to water reuse projects in the agricultural sector. Racar et al. (2020) evaluated the use of MBR followed by NF/RO for crops irrigation, comparing with the WHO and EU 2020/741 guidelines the removal of main physico-chemical and microbiological parameters, and including also a revision of the detection and removal of organic micropollutants included in the Watch List (EU Decision 2015/495). Additionally, Nahim-Granados et al. (2020) assessed from a techno-economic perspective the implementation at industrial scale of different solar-based water purification processes for OMP removal and disinfection. Mendret et al. (2019) investigated the use of ozonation and RO for urban wastewater reclamation for a capacity of 125 m^3/h and assessed the economic savings of the potential reuse of the effluent. Moreover Uludag-Demirer et al. (2020) investigated Electrocoagulation for the reclamation of anaerobic digestion effluents, providing results of physico-chemical and microbiological parameters removal, as well as estimating its cost; and Zarebska-Molgaard et al. (2022) studied also the application of a combination between forward osmosis (FO) and Membrane Distillation (MD) to reclaim anaerobic digestion effluents, evaluating also generic costs.

Valuable information for the definition of DSS was obtained by Murashko et al. (2018) when analysed the potential of implementing a closed-loop decentralized wastewater treatment and reclamation plant in a Finnish community. Four different scenarios were assessed considering two different technological setups, in which costs are estimated and compared in terms of CAPEX and OPEX. These results can be used to support the investment decision regarding different technological alternatives considering a fixed capacity; nevertheless, as well as previous mentioned works, these results do not consider the differences associated to scale and the added complexity of providing different qualities regarding considered uses.

Regarding promoting reuse in the industrial sector, Saidan (2020) quantified the water demand and reclamation needs in 395 industrial facilities in Jordan through a cross-sectional survey, obtaining valuable results regarding water consumption per employee and per ton of product, as well as wastewater disposal practices. Nevertheless, although potential volumes to be reused were identified, a very preliminary techno-economic analysis was provided, avoiding details on which technologies should be implemented and their CAPEX and OPEX. Wang et al. (2019) assessed the use of moving bed ceramic membrane bioreactor (MBCMBR) and reverse osmosis (RO) for municipal wastewater reclamation considering ultrapure water standards to be supplied to various industrial sectors in Singapore. In a similar work, Liu et al. (2020) assessed the use of an anaerobic fixed-film membrane bioreactor (AnfMBR) followed by RO for municipal water reclamation and compared its costs towards the existing NEWater facility in Singapore, concluding that about 37.5% reduction in total cost could be achieved due to an improvement in energy efficiency. Additionally, Shingwenyana et al. (2021) investigated a circular economy concept in the South African mining sector, specifically in the reclamation and valorization of acid mine drainage (AMD). CAPEX and OPEX was provided for a softening process followed by RO.

In a similar way to the present study, Pérez et al. (2022) evaluated a decentralized UF + RO system for municipal water reclamation in an industrial hub located nearby the Vuelta Ostrera WWTP (Spain). The authors assessed the optimal operational conditions and estimated the associated costs (CAPEX and OPEX) for three different scenarios (2.5, 5 and 20 m^3/h) as well as potential savings regarding the current water cost.

5. Conclusions

The technical feasibility of the evaluated polishing treatment trains has been demonstrated through the operation and optimization during eighteen months of a treatment train located in El Baix Llobregat WWTP. Both pre-treatments, UF and CNM, allowed the removal of SS and turbidity, and a similar removal of dissolved organic matter. No significant differences were found in the RO performance in terms of organic fouling or scaling, regardless of the pre-treatment (UF or CNM) applied. In the case of CNM effluent, a permeability decline in RO of 5% was found, while in the case of UF effluent permeability remained steady.

On the other hand, regarding OMP, the use of advanced adsorbents allowed high removals of triazines (67% and 97% for Terbuthylazine and Atrazine respectively), while as expected UF presented relatively low removal efficiencies ($\leq$25%).

Water quality requirements for the different uses of each of the three industrial sites have been gathered. The removal of dissolved salts (limited as maximum conductivity or chloride concentration) and hardness are the main requirements for most of the uses evaluated, as well as some limitations in COD or TOC. This clearly demands the use of desalination technologies such as RO, as it has been exposed in the full-scale treatment trains projection. On the other hand, it points out the non-alignment between regulation and end-users requirements.

The economic feasibility has been evaluated for the three industrial scenarios, considering the water qualities and insights obtained from the prototype performance. In this line, the calculation of cost curves for both CAPEX and OPEX has allowed the estimation of economic scenarios for the three sites, considering both treatment schemes combinations (UF followed by RO and CNM/GAC followed by RO). Based on the results obtained, potential savings have been estimated considering the current cost of water accounted by the industrial users, and the estimated tariff of municipal reclaimed water that would fed the decentralized treatment.

The assessment indicates that the use of municipal reclaimed water for industrial applications is economically competitive in front of the use of tap water, which has the need to add polishing steps such as IEX or RO. On the other hand, the use of groundwater and its relatively low cost implied that, although it is necessary a RO step, the current cost of water is significantly lower than the one assumed for the water reuse project.

Beyond the economic results, and the fact that in one of the three cases the water reuse project was unfeasible from a cost perspective, other drivers need to be considered such as the preservation of freshwater resources and resilience strategies in front of climate change to guarantee water supply and industrial production.

CRediT authorship contribution statement

Carlos Echevarría: Investigation, Conceptualization, Methodology, Formal Analysis, Writing-Original Draft, Visualization. **Mateo Pastur**: Investigation, Formal Analysis, Prototypes Operation. **Jose Luis Cortina**: Conceptualization, Validation, Writing - Review & Editing, Supervision. **Cesar Valderrama**: Conceptualization, Validation, Writing - Review & Editing, Supervision. **Alex Vega**: Resources, Methodology, Writing - Review & Editing, Supervision, **Cristian Mesa**: Resources, Writing - Review & Editing, Supervision. **Mercè Aceves**: Resources, Methodology, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152842.

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