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Pilot-scale demonstration of advanced wastewater treatment for direct potable water reuse for beer production☆

Rui M.C. Viegas [a,*], David Figueiredo [b], Elsa Mesquita [a], Sofia Charrua [a,b], Carla Costa [c], Rita Lourinho [b], Maria João Rosa [a]

[a] Urban Water Unit, Hydraulics and Environment Department, LNEC – National Laboratory for Civil Engineering, Av. Brasil 101, 1700-066 Lisbon, Portugal
[b] Águas do Tejo Atlântico (AdTA), Wastewater Utility, ETAR de Alcântara, Avenida de Ceuta, 1300-254 Lisbon, Portugal
[c] Moinhos Água e Ambiente, Zona Industrial Alto da Cruz, Rua B 66, 4780-739 Santo Tirso, Portugal

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ABSTRACT

To foster public trust in water reuse and develop solutions for future water scarcity, the B-WaterSmart project piloted water reclamation for artisanal beer production, providing scientific evidence on the safety of direct potable reuse (DPR) in industry. The demonstration took place at the Beirolas Water Resource Recovery Facility in Portugal, where four advanced treatment technologies were tested: ultrafiltration (UF), ozonation (O_3), biologically active granular activated carbon (BAC) filtration, and reverse osmosis (RO). Four RO-based reclamation schemes were continuously piloted (24/7) to assess water quality and operational performance: (1) UF + O_3 + RO, (2) UF + RO, (3) UF + O_3 + BAC + RO, and (4) O_3 + BAC + RO. Water quality was monitored weekly for *E. coli*, organic matter and nutrients, and, once per scheme, for trace compounds, including 54 pharmaceutical compounds (PhCs), 2 hormones, oxidation by-products (N-Nitrosodimethylamine (NDMA), bromate, chlorate, 4 trihalomethanes (THMs), 9 haloacetic acids (HAAs)), 20 per- and polyfluoroalkyl substances (PFAS), 10 alkylphenols, and toxicity (*Daphnia magna*, *Vibrio fischeri*). EU Drinking Water Directive 2020 parameters and pathogen indicators (*Clostridium perfringens*, enteric viruses, protozoa) were also assessed. All treatment schemes produced water meeting EU and Portuguese drinking water standards, with no pathogen indicators and with trace contaminants below quantification limits (PFAS < 2 ng/L, 5 HAAs < 1 μg/L, bromate < 3 ng/L, PhCs < 0.3 μg/L) or below international regulations or guidelines (total THMs < 2 μg/L, NDMA < 8 ng/L). Operational monitoring showed lower energy demand for the UF + RO scheme, corresponding to 1.0 kWh/m^3. Furthermore, a craft beer company used the produced water to brew 1000 L of beer, which received a positive organoleptic evaluation from its producer.

1. Introduction

Climate change and climate variability are intensifying droughts and floods, placing increasing pressure on global water resources. Currently, water scarcity affects 17 % of the European Union's territory and 11 % of its population, demonstrating that this challenge is no longer confined to southern Europe [1,2]. Factors such as rapid urbanization, population growth, economic expansion (including agriculture, industry, tourism, and renewable energy), and stress on catchment areas are further straining drinking water supplies. These growing pressures highlight the urgent need to identify new or alternative sources of supply [3].

Water reuse has emerged as a viable solution, with potable applications already implemented in countries such as Australia, Namibia, the United States, Singapore, and Israel [4]. While non-potable reuse is more widespread, potable reuse remains a complex endeavour due to concerns over microbial and chemical contaminants. This process typically requires advanced treatment technologies and stringent management practices to ensure safety and reliability [3].

Potable reuse can be categorized into two main types: direct potable reuse (DPR) and indirect potable reuse (IPR). DPR involves introducing highly treated wastewater directly into a water supply system, whereas IPR first discharges the treated water into an environmental buffer, such

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* Corresponding author.
E-mail addresses: rviegas@lnec.pt (R.M.C. Viegas), david.figueiredo@adp.pt (D. Figueiredo), emesquita@lnec.pt (E. Mesquita), carla.costa@moinhosambiente.com (C. Costa), rita.lourinho@adp.pt (R. Lourinho), mjrosa@lnec.pt (M.J. Rosa).

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as an aquifer or reservoir, before re-entering the supply system [5]. DPR offers advantages over IPR, including reduced contamination risks in environmental buffers, lower pumping and transport costs, and applicability in regions where environmental buffers are unavailable [6,7]. However, DPR also poses challenges, such as the absence of a natural barrier, which reduces response time to potential treatment failures.

Globally, most potable reuse projects involve IPR, while DPR remains in earlier stages of implementation, with fewer operational facilities [8,9]. Most potable reuse installations are in the United States, with additional projects in Australia, Singapore, and Southern Africa (Namibia and South Africa). IPR plants are far more numerous than DPR, and the large IPR installations are mostly in Southern California, which has its first installation operating since 1962, Singapore and Australia [9]. In Europe, IPR plants are operational in Belgium (since 2002) [10] and Spain [11]. As for DPR, the Goreangab Water Reclamation Plant in Windhoek, Namibia, remains the world's longest-running DPR facility, in operation since 1969 [9,10]. Limited DPR installations exist in the USA, South Africa, and Sweden, the latter being the only known DPR facility in Europe [9].

One novel application of DPR is its use in craft beer production. While small pilot projects exist worldwide, the most notable initiative is the Pure Water Brewing Alliance [12], a collaboration of utilities, consultants, professional associations, and craft brewers that have been producing beer from reclaimed water since 2017. Deionized and dechlorinated water offers advantages in beverage production, and beer brewing itself introduces additional safety barriers that further ensure the final product quality. The brewing process includes mashing, boiling, cooling, fermenting, maturing, and bottling. During mashing, milled malt is mixed with water (in this case, reclaimed potable water) under controlled conditions to convert starch into sugar. Hops are added during boiling to enhance flavour and aroma, followed by cooling, fermentation (where yeast converts sugars into alcohol and carbon dioxide), and pasteurization during bottling. These sequential steps create multiple barriers that enhance microbial safety, reinforcing the viability of DPR-treated water for brewing.

Ensuring public health protection in potable reuse requires removing microbiological and chemical contaminants to safe levels. While complete elimination is impractical (and not measurable), regulatory frameworks set exposure limits to minimize health risks. However, DPR regulations vary significantly across regions. In the United States, the Environmental Protection Agency (USEPA) provides guidance through the Water Reuse Action Plan [13], and organizations like the WateReuse Research Foundation [5] and the World Health Organization (WHO) [3] offer best practices. These guidelines often serve as references for countries developing their own regulations, e.g. Singapore and Namibia. Despite growing global interest, the regulatory landscape remains fragmented, with standards evolving based on local conditions and priorities.

This study, conducted within the B-WaterSmart project, aims to contribute pilot-scale data to support the development of DPR guidelines, focusing on water quality, operational performance, and system redundancy for the safe production of reclaimed water suitable for craft beer brewing. A containerized pilot unit, featuring an external cork coating and photovoltaic energy production, was installed at the Beirolas Water Resource Recovery Facility (WRRF) in Portugal — one of the country's largest facilities. Four advanced treatment technologies were tested: ultrafiltration (UF), ozonation (O_3), biologically active granular activated carbon (BAC) filtration, and reverse osmosis (RO). To compare different RO-based reclamation schemes regarding water quality and operational performance, four treatment schemes were continuously (24/7) piloted, sequentially, for one year: (1) UF + O_3 + RO, (2) UF (+Cl_2) + RO, (3) UF(+Cl_2) + O_3 + BAC + RO, (4) O_3 + BAC + RO.

As in Portugal potable water reuse is not considered nor regulated, this study adhered to drinking water quality standards outlined in the Portuguese regulation [14] transposing the European Union Drinking Water Directive (DWD 2020). For other parameters, namely for non-regulated contaminants of emerging concern (CECs), the "Guidelines for Drinking-Water Quality" from the World Health Organization [15] and the "Examining the criteria for direct potable reuse" of the National Water Research Institute and of the WateReuse Research Foundation [16] were used.

By demonstrating the feasibility of DPR for craft beer production, this research seeks to establish potable reuse as a viable solution for water scarcity, localized needs, and emergency situations while fostering public confidence in water reuse safety.

2. Experimental section

2.1. Water resource recovery facility description

The pilot unit was installed at the Beirolas Water Resource Recovery Facility (WRRF) which has been in operation since 1989. It serves the municipalities of Lisbon and Loures and discharges the treated effluent into Tagus River Estuary Natural Reserve, the largest estuary in western Europe. The facility serves a population equivalent of 213,540 inhabitants, with an average daily flow rate of 54,500 m^3/d, and it has the capability to treat a peak flow rate of 3000 m^3/h, during dry weather and a peak flow rate of 4600 m^3/h in wet weather conditions. The wastewater is predominantly domestic, with a relatively minor industrial contribution. During high tide levels in the estuary, salt intrusion occurs in the sewage network, reaching the WRRF.

The wastewater treatment process begins with pre-treatment, which includes coarse solids screening, sand removal and degreasing. Subsequently, it progresses to primary treatment with primary sedimentation clarifiers and then to an equalization tank. The secondary treatment includes an anaerobic/anoxic/oxic (A2O) activated sludge system for biological treatment, followed by secondary clarifiers. Afterwards, the wastewater undergoes filtration through sand filters before being discharged into the Tagus Estuary. The quality requirements of discharge permit are shown in Table 1.

In addition, the WRRF features two water reclamation lines for irrigation, street cleaning and internal reuse (Fig. S.1). The one designed for internal uses includes 50 μm microfilters, UV disinfection and sodium hypochlorite dosing, and the reclaimed water must meet Class B requirements outlined in the Portuguese Decree-Law No. 119/2019, of August 21 [17].

The other reclamation line is dedicated to external uses, such as public greenspaces unrestricted irrigation within the Lisbon Municipality. This line is also equipped with 50 μm microfilters, an UF system with 20 membrane modules (polymer hollow fibre membranes, 0.04 μm pore, DuPont), and sodium hypochlorite dosing (Fig. S.1). The UF system has the capacity to treat 1200 m^3/d and during the demonstration was operated with a transmembrane pressure (TMP) of 0.5–0.6 bar. The reclaimed water must meet Class A requirements outlined in the

Table 1
Quality requirements for Beirolas WRRF effluent and reclaimed water for internal and external uses..

Parameter	Unit	Beirolas WRRF effluent	Reclaimed wáter internal uses Class B	Reclaimed wáter external uses Class A
Chemical oxygen demand, COD	mg O_2/L	≤125	–	–
5-day biochemical oxygen demand, BOD_5	mg O_2/L	≤25	≤25	≤10
Total suspended solids, TSS	mg/L	≤35	≤35	≤10
E. coli	CFU/100 mL	–	≤100	≤10
Turbidity	NTU	–	–	≤5

Source: Portuguese Decree-Law No. 152/97 and Decree-Law No. 119/2019

Portuguese DL 119/2019 (Table 1), which is in line with the EU regulation [18].

The pilot treatment line could be fed with the three sources of water in Table 1, i.e. Beirolas WRRF effluent, reclaimed water Class B, and reclaimed water Class A. However, during the project demonstration, only the effluent from the Beirolas WRRF and the Class A reclaimed water were used. The average quality of these sources during 2023 is detailed in Table 2.

2.2. Direct potable reuse pilot unit

The pilot unit was installed in a container featuring an outer cork coating for insulation and incorporating a photovoltaic panel system for energy self-consumption (Fig. S.2).

The potable reuse pilot comprised four advanced treatment technologies: O_3, BAC filtration, and a 3-stage RO system. UF did not integrate the pilot plant, it is implemented at the WRRF for reclaimed water production for unrestricted urban irrigation.

The pilot unit had a production capacity of 1250 L/h and was designed for a continuous and automated treatment process, allowing remote monitoring of several operational parameters. The combination of the treatment processes can be switched. A simplified diagram is provided in Fig. 1.

2.2.1. Ozonation

The ozonation system was equipped with a WEDECO EFFIZON GSO 10/20 ozone generator, capable of converting oxygen (liquid oxygen provided by Nippon gases, at a minimum of 99.5 %) into ozone with a production capacity of 30 g O_3/h, an ozonation contact chamber that includes a high-pressure pump and a hydro-injector for ozone dissolution, and a Venturi injector that achieves an ozone transfer efficiency of over 90 %.

This system was designed to provide a variable ozone dose (5–10 mg O_3/L were tested, corresponding to 1–2 mg O_3/mg total organic carbon (TOC), with a contact time of approximately 45 min. The chamber was fed with 1.7–1.8 m^3/h of water. A turbidimeter was installed at the inlet of the ozone chamber and a redox potential probe after the chamber. At this stage, sodium bisulfite ($NaHSO_3$, 38.5 %) could be dosed for neutralizing oxidizing agents (ozone or free chlorine residuals) that otherwise could damage the membranes.

Following the ozone chamber, a feed tank was placed to maintain a consistent feed to the RO system. It was designed for a contact time ranging from 84 to 98 min, allowing for the decay of residual ozone in the treated water, considering the limitations associated with reverse osmosis membranes in handling feedwater containing oxidizing agents. The oxidation reduction potential (ORP) was online monitored, and the dosing of sodium bisulfite would be triggered if it exceeded 250 mV (maximum recommended by the manufacturer), which did not prove to be necessary.

Table 2
Average quality of Beirolas WWRF effluent and of Class A reclaimed water, during 2023.

Parameter	Unit	Beirolas WRRF effluent	Class A reclaimed water
COD	mg O_2/L	37.6	N/A
BOD_5	mg O_2/L	6.0	< 6.0
TSS	mg/L	4.4	<3
Total nitrogen, TN	mg N/L	13.0	11.9
Ammonium	mg NH4/L	3.8	2.3
Nitrates	mg N/L	7.9	6.9
Total phosphorous, TP	mg P/L	4.0	3.4
E. coli	CFU/100 mL	3×10^3	0
Turbidity	NTU	–	<0.1

Source: Águas do Tejo Atlântico.

2.2.2. Biologically active carbon filtration

Following the feed tank, a granular activated carbon (GAC) column filter featuring an activated carbon with an 8 × 30 mesh, WT 830 from Media Carb, Switzerland, was installed. This activated carbon is derived from bituminous coal and steam activated. The prolonged operation of the GAC as well as its combination with ozone foster the biological properties of the GAC, thus converting it into a biologically active carbon (BAC) filtration system.

The bed volume of the BAC system was approximately 137 L, providing an empty bed contact time (EBCT) of around 5 min. Throughout the demonstration, the system was in operation for 31 thousand bed volumes (kBV), which translates to approximately 3.5 months of continuous operation.

2.2.3. Reverse osmosis

After the BAC filter, there was a set of two parallel microfilter cartridges (Wasser) made of melt-down polypropylene fibres to protect the RO system, including from the GAC filter fines. The RO system had a 3-stage configuration with a 2:1:1 vessel arrangement with recirculation. Each vessel comprised 2 RO polyamide composite membranes, Hydranautics CPA5-LD-4040, offering high salt rejection, exceeding 99.5 % for NaCl. The system included eight membrane modules with a total membrane area of approximately 60 m^2. The water recovery rates (WRR) for this system were set at 70 % or 60 %, depending on the operational performance. The RO operated automatically to produce a constant permeate flow rate of 1250 L/h (at 70 % WRR) or 1000 L/h (at 60 % WRR). During the demonstration, RO was operated with a feed pressure between 7.2 and 14.9 bar, much depending on the feed salinity.

For scaling prevention, an antiscalant was dosed (Genesys LF, 3 mg/L) at the inlet of the microfilters, and acid dosing was also an option. For biofouling control, sodium hypochlorite (13 %, as received, further diluted to 1.95 %) was occasionally (in some trials) dosed to the RO feed tank, with a set-point of 0.9 mg Cl_2/L. Chlorine was monitored for free chlorine and total chlorine, by the DPD (N,N-diethyl-p-phenylenediamine) method [19], at the pilot inlet and at the membranes' inlet. Additionally, clean-in-place (CIP) was conducted regularly for cleaning and maintenance, helping to ensure the longevity and optimal performance of the system. Depending on the foulants, alkaline CIP or acid CIP were performed, according to the membrane's specification.

In both CIP procedures, the RO system was firstly rinsed with the RO permeate. For acid CIP, a solution with Auxiclean A – 1.6 was prepared with a temperature between 35 °C and 40 °C, while adjusting the pH at 2. For alkaline CIP, a solution with Auxiclean B-13 was prepared with a temperature between 35 °C and 40 °C, while adjusting the pH at 12. In both cases, the solution was recirculated for approximately 2 h while monitoring temperature and pH. At the end of each CIP, a thorough rinse was carried out to remove any remaining contaminants or detergent residues.

2.3. Direct potable reuse treatment schemes

Four advanced potable reuse schemes were tested, following a multi-barrier treatment approach. The schemes, illustrated in Fig. 2, were specifically designed to include multiple barriers in addition to the conventional treatment of WRRF, mainly to address:

- suspended solids (UF, BAC, and RO, besides the full-scale sand and 50-μm filters);
- microbiological contaminants (UF, ozonation, chlorination, and RO);
- dissolved chemicals and trace organic compounds (ozonation, BAC, and RO).

Scheme 1.

This potable reuse scheme included three treatment barriers: UF, ozonation, and RO. The pilot included an UF unit, an ozonation chamber, a feed tank, 5 μm microfilters, and a 3-stage RO system. In this

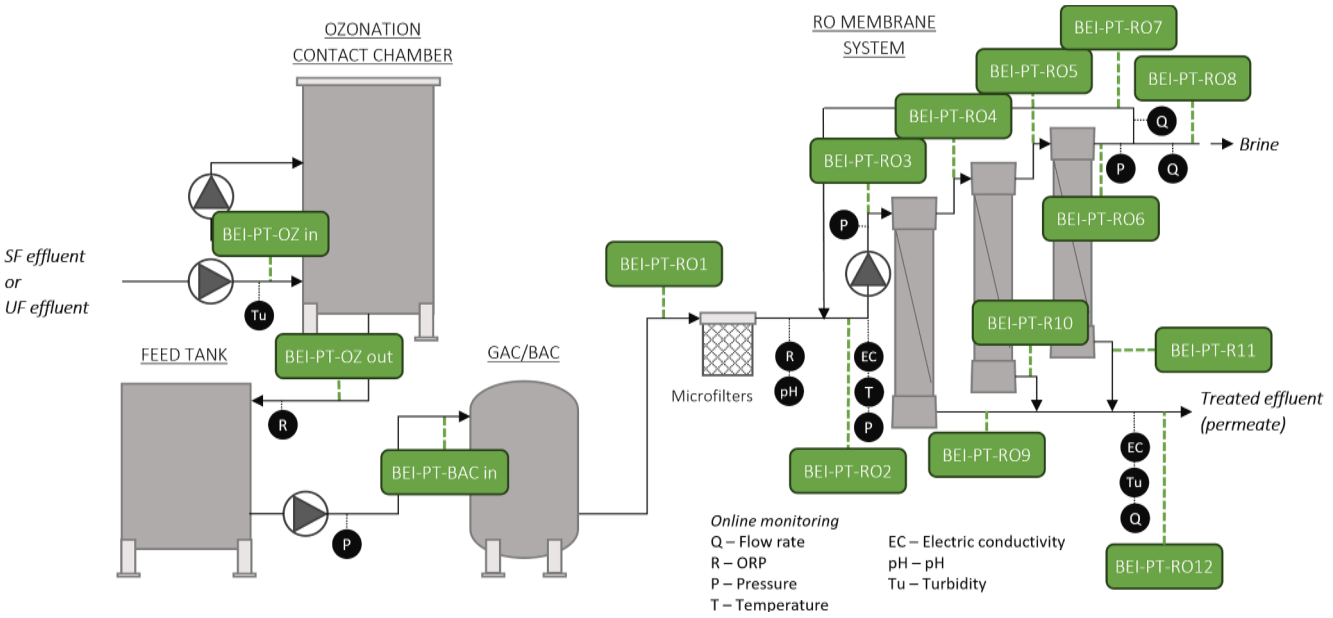

Fig. 1. Pilot unit system diagram and operational monitoring points (in the green boxes).

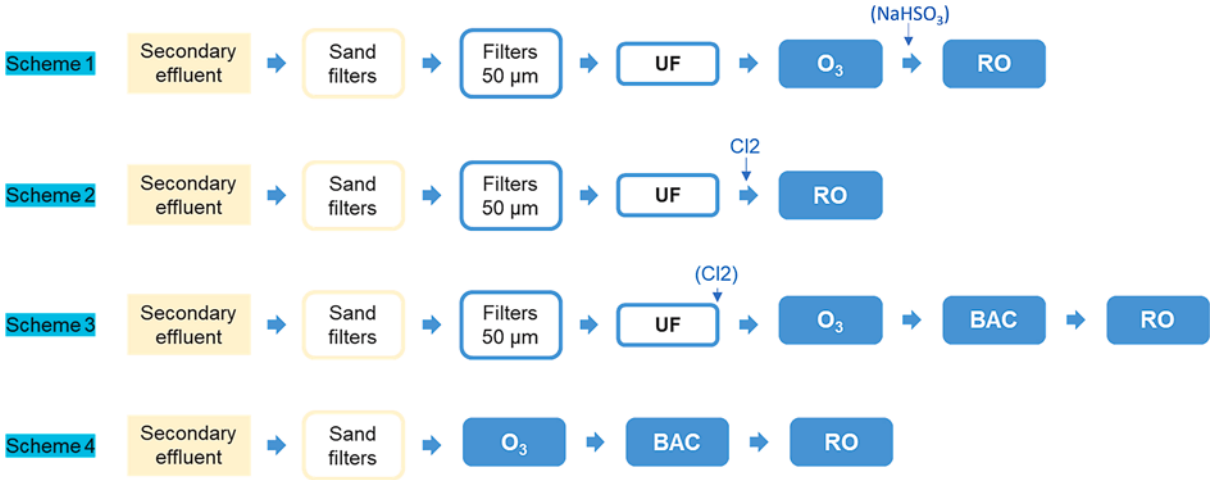

Fig. 2. Potable reuse schemes tested and demonstrated.

scheme, the RO system was operated at a 70 % WRR, yielding a permeate flowrate of 1.25 m^3/h.

Scheme 2.

This potable reuse scheme included three treatment barriers: UF, chlorination, and RO. Downstream the UF unit, chlorine was dosed in low concentrations (0.9 mg/L) to prevent biofouling and no ozonation was included before the final RO step. In this scheme, the RO system was operated at 70 % WRR, 1.25 m^3/h permeate flowrate, and at 60 % WRR, 1 m^3/h.

Scheme 3.

This potable reuse scheme included five treatment barriers: UF, chlorination, ozonation, BAC, and RO. Chlorine was dosed (at 0.9 mg/L) after the UF treatment step, and a BAC filter was installed between ozonation and RO stages. RO was operated at 60 % WRR, 1 m^3/h.

Scheme 4.

This potable reuse scheme included three treatment barriers: ozonation, BAC, and RO, described above. RO was operated at 60 % WRR, 1 m^3/h.

2.4. Monitoring

A comprehensive monitoring and control system is necessary to measure and track the performance of potable reuse schemes, to ensure that operational targets are being met [3]. Monitoring needs to be undertaken at a frequency that will enable rapid and timely responses if significant deviations occur that could affect water quality. Tiered operational monitoring programs that emphasize expedite methods or online measures with real-time data reporting are critical so that anomalies can be rapidly detected, and measures can be accordingly taken on time [3].

The monitoring strategy involved water quality monitoring and operational monitoring, the latter including the system integrity.

2.4.1. Water quality monitoring

The monitoring activities took place during the pilot demonstrations, spanning from April 2023 to March 2024. During this period, more than 200 microbiological analyses and 4000 chemical analyses, including CECs and disinfection by-products (DBPs), were performed.

The monitoring plan included regular analytical monitoring,

performed once or twice a week, and extended analytical monitoring, carried out once for each scheme.

2.4.1.1. Sampling points. The different sampling points for water quality monitoring are identified in Fig. 3. Their verification provides an assessment of the effectiveness of the pilot system in achieving compliance with health-based targets.

2.4.1.2. Microbiological parameters. Monitoring microbial pathogens in water produced by potable reuse schemes is impractical and often of little value [3]. The traditional approach to verify microbial water quality is the use of faecal contamination indicators such as *E. coli*, and this approach was used in this pilot demonstration, with the regular monitoring of *E. coli* once a week. A limitation of *E. coli* is that it is not a particularly good indicator of enteric viruses and protozoa or other enteric bacteria, which are more resistant to environmental pressures. As such, other indicators were included in the extended analytical monitoring for each scheme, namely somatic coliphages and F-specific RNA bacteriophages (for enteric viruses), *Clostridium* spp. spores (for protozoa), *Clostridium perfringens* and enterococci (for enteric bacteria more resistant than *E. coli* to chemical disinfection). Some of these parameters are also foreseen in the DWD 2020 [20] with parametric values. Colony count at 22 °C and coliform bacteria completed the extended monitoring. Since RO is a physical barrier against bacteria and genes by size-exclusion, the selected microbial indicators are also surrogates of microbial parameters of emerging concern, e.g. antibiotic-resistant bacteria and antibiotic-resistance genes, which were then not monitored. The monitoring plan for microbiological water quality includes the parameters listed in Table S.1 for the sampling points identified in Fig. 3, where applicable, depending on the scheme under operation.

2.4.1.3. Chemical parameters. Since no regulation exists for direct potable reuse in Portugal or in the EU, all the chemical parameters included in the DWD 2020 [20] were monitored. To increase the confidence by operators and consumers in the water safety, other disinfection by-products and a wide range of contaminants of emerging concern were also monitored.

The monitoring plan for chemical water quality includes the parameters listed in Table 3 for the sampling points identified in Fig. 3, where applicable, depending on the scheme in operation.

Table 3
Chemical parameters included in the monitoring plan.

Monitoring type/frequency	Parameter
Regular analytical monitoring once or twice a week	Electrical conductivity and pH Turbidity and ORP Organic matter parameters (total organic carbon (TOC), dissolved organic carbon (DOC), absorbance at 254 nm (A254), absorbance at 436 nm (A436), specific UV absorbance (SUVA)) NH_4, NO_3, KN, TN, TP Hardness Alkalinity
Extended analytical monitoring once for each scheme (carried out on 06/06/2023, 27/07/2023, 21/11/2023, 12/03/2024)	54 Pharmaceutical compounds (PhCs) Estrogenic hormones: 17-β-estradiol and 17-α-ethinylestradiol Bisphenol A 10 Alkylphenols 20 per- and polyfluoroalkyl substances (PFAS), incl. PFOS, PFOA, PFOSA Toxicity (*Daphnia magna* + *Vibrio fisheri*) Bromide Bromate, chlorite and chlorate N-Nitrosodimethylamine (NDMA) 4 Trihalomethanes (THMs) 9 Haloacetic acids (HAAs) Drinking Water Directive 2020 parameters*

* The identified parameters were only analysed at the sampling point BEI-PT-RO12, which is the final potable water for craft beer production.

2.4.2. Operational monitoring

According to WHO [3], having monitoring data available to prevent and correct deterioration of the performance of each unit barrier in a potable reuse scheme is the key for assuring consistent production of safe water. Monitoring of unit processes at control points within a treatment train requires identification of appropriate parameters and target criteria to define operational performance acceptability. Target criteria can take the form of operational limits and critical limits. Critical limits for treatment processes used in potable reuse separate acceptable from unacceptable performance and loss of confidence in water safety. Depending on the nature of the control measure, critical limits can be upper limits (e.g., maximum filtered water turbidity), lower limits (e.g., minimum disinfectant Ct values) or ranges of values (e.g., pH range).

Operational limits are typically used as early-warning signals that performance of control measures is deteriorating and that corrective actions must be implemented. Considering the above mentioned, the operational monitoring points (Fig. 1) and the corresponding parameters and target criteria were defined.

According to WHO [3], in potable reuse schemes, pathogen control is achieved by a combination of inactivation processes and physical removal; therefore, the most widely used operational monitoring parameters are disinfectant residuals and physical removal of, e.g., turbidity, both parameters monitored online. Membrane integrity needs also to be monitored. Following international best practices, in this case, the UF membranes integrity was assessed by online turbidity measurements and periodic pressure decay tests [21] and the RO membranes integrity was monitored by online measurement of electrical conductivity (representing total dissolved solids (TDS) rejection) and total organic carbon (TOC) [3]. Other parameters, such as pH and turbidity are also important for ensuring effective disinfection and were regularly monitored.

For operational monitoring of chemical compounds' removal, the most suitable approach recommended by WHO [3] was adopted, i.e., the performance was measured through bulk parameters that can be monitored using online monitoring or high-frequency grab samples and can be used for real-time decision-making for process control, namely TOC and electrical conductivity.

Considering the above, the operational monitoring of this specific pilot unit included the parameters and target criteria listed in Table 4.

Three performance indicators were additionally computed during the demonstration to diagnose the RO system operation and cleaning needs: (i) Normalized permeate flow (or membrane permeability, i.e., permeate flow normalized for temperature and pressure, function of the feedwater temperature, feed and permeate pressures and feedwater TDS); (ii) Normalized salt passage; (iii) Normalized pressure drop (ΔP,

Fig. 3. Water quality monitoring sampling points.

Table 4
Operational monitoring points of the pilot unit, associated parameters and target values.

Operational monitoring point	Parameter	Type of measurement	Acceptable value/range
BEI-PT-OZ in	Turbidity	Online	–
	Flow rate	Occasional	1.8 m^3/h (set-point)
BEI-PT-OZ out	ORP	Online	≥500 mV, when ozonation is working
BEI-PT-BAC in	Pressure	Online	<0.5 bar pressure increase (vs. initial pressure)
BEI-PT-RO1	Pressure	Occasional	<0.5 bar pressure gradient between the microfilters inlet/outlet
	ORP	Online	<250 mV
	pH	Online	–
BEI-PT-RO2	Pressure	Online	>1.5 bar
	Temperature	Online	<45 °C
	Conductivity	Online	–
BEI-PT-RO3	Pressure	Online	–
BEI-PT-RO4	Pressure	Occasional	–
BEI-PT-RO5	Pressure	Occasional	–
BEI-PT-RO6	Pressure	Online	–
BEI-PT-RO7	Flow rate	Online	0.50 m^3/h (set-point) – for 70 % WRR 0.90 m^3/h (set-point) – for 60 % WRR
BEI-PT-RO8	Flow rate	Online	0.54 m^3/h (set-point) – for 70 % WRR 0.67 m^3/h (set-point) – for 60 % WRR
BEI-PT-RO9	Conductivity	Occasional	–
BEI-PT-RO10	Conductivity	Occasional	–
BEI-PT-RO11	Conductivity	Occasional	–
BEI-PT-RO12	Conductivity	Online	<50 µS/cm
	Turbidity	Online	<0.1 NTU
	Flow rate	Online	1.25 m^3/h – for 70 % WRR 1.00 m^3/h – for 60 % WRR

the difference between the inlet to the first membrane elements and the concentrate stream pressure coming off the tail end elements of each stage or train). Target values for starting RO membrane cleaning were a Normalized permeate flow decrease >10 %, a Normalized salt passage increase >10 % and a Normalized pressure drop increase >15 %.

2.5. Analytical methods

Several internal and externally contracted laboratories were involved in the determination of the 186 parameters monitored during this 1-year pilot demo, using standard and accredited methods whenever possible, as detailed in Table S.2 and Table S.3 (additional parameters from DWD 2020).

3. Results and discussion

During the demonstration, more than 6500 analyses were performed for 186 parameters, of which >60 are CECs. A summary of all analytical results (chemical and microbiological) is presented in Supplementary material, Table S..4 to Table S..7.

3.1. Microbiological water quality results

During the pilot demonstration, around 200 microbiological analyses were conducted. None of the microbiological parameters were detected in any of the finished waters for craft beer production across all schemes. Regarding *E. coli*, *Clostridium perfringens* and its spores, they were only detected after ozonation in scheme 4, which did not include UF. In this scheme, the ozonation with 2 mg O_3/mg TOC did not act as a complete barrier, but the RO successfully prevented the presence of these microbial indicators in the finished water. In the other schemes, UF proved to be an effective barrier against these indicators. Additionally, somatic coliphages and F-specific RNA bacteriophages were never detected, neither at the inlet nor at the outlet of all schemes.

With respect to the treatment process efficiency, measured as log-reduction values (LRVs) of microbial indicators, this study was conducted with no spiking, to fully represent the real environment. Therefore, the removal of naturally occurring pathogens was limited by their low feedwater concentration. For example, regarding *E. coli*, the UF treated water (schemes 1, 2, and 3, in a total 30 analyses) showed values below the limit of quantification (LOQ, 1 CFU/100 mL), except during the commissioning phase (scheme 2), when a value of 3 CFU/100 mL was observed. The sand-filtered effluent varied from $3x10^3$ to $3x10^5$ CFU/100 mL and thus the LRVs obtained with UF were limited by these intake values, varying between >3.5 and >5.2, values fully aligned with the indicative LRVs compiled in [22], i.e., 4 to >6 LRV. When UF was not part of the treatment train (scheme 4) and ozonation was the first barrier, the tested ozone dose of 2 mg O_3/mg TOC was not always fully effective for *E. coli* inactivation (values between 1 (LOQ) and 23 CFU/100 mL were observed after ozonation), but the calculated LRVs, between 1.8 and >3.4, were also aligned with the indicative LRVs compiled in [22], i.e. 2–6.

Regarding the other microbial indicators analysed, i.e. *Clostridium perfringens* and its spores and Somatic coliphages, UF was fully effective for their removal. Nevertheless, as the sand-filtered effluents (UF inlet) were not analysed, the UF LRVs could not be assessed. In scheme 4, ozonation was not fully effective for inactivating *Clostridium perfringens* and its spores, as expected ([22]), being observed values of 800 CFU/100 mL and 520 CFU/50 mL, respectively. Somatic coliphages were not detected in any of the 11 samples analysed.

3.2. Chemical water quality results

In the demonstration, a multitude of chemical analyses were conducted (>6300 analyses, Table S.4 to Table S.7), and a summary of the key findings is herein presented.

3.2.1. Per- and polyfluoroalkyl substances

In Figs. 4–7, the concentrations of detected PFAS throughout each of the schemes are presented, as well as the corresponding removal rates. Nine PFAS were never detected and the remaining 11 were always below LOQ (0.3, 0.6, 1, or 2 ng/L). A higher occurrence of perfluoroalkyl carboxylic acids, both short- (PFPeA and PFHxA) and long-chain (PFOA) PFAS was observed, as previously reported [23]. Across all potable reuse schemes, the concentrations of the individual PFAS and the sum of 20 PFAS in the potable water for craft beer production are below the corresponding LOQs, which are far below the DWD 2020 parametric value of 100 ng/L. The removal rates of each potable reuse scheme and of RO were limited by the LOQ values.

For the detected PFAS, ozonation showed low and variable removal rates: in scheme 1, removals of 0–8 % were observed; in scheme 3, the removals attained 17 % (PFOA); in scheme 4, removals up to 41 % were observed (PFPeS). Nonetheless, ozonation appears to have contributed to the formation of the short-chain PFPeA (more noticeable), PFHxA, and PFHpA. These low removals or even formation/transformation of these “forever chemicals” are in line with other published results [24].

The BAC filter showed PFAS removals in the range of 0–38 % in scheme 3 and of 0–26 % in scheme 4, and higher for long-chain PFAS, both carboxylates (PFDA, PFNA, PFOA) and sulfonates (PFOS, PFHxS). These removals were, nevertheless, lower than in other published results, which report complete elimination (>90 %) of PFOA [23], though for an EBCT of 20 min.

3.2.2. Pharmaceutical compounds

In Figs. 8–11, the concentrations of detected PhCs throughout each of the schemes are presented, as well as the corresponding removal rates. Twenty-five out of the 54 pharmaceutical compounds analysed were never detected. Diclofenac, hydrochlorothiazide, iomeprol, and

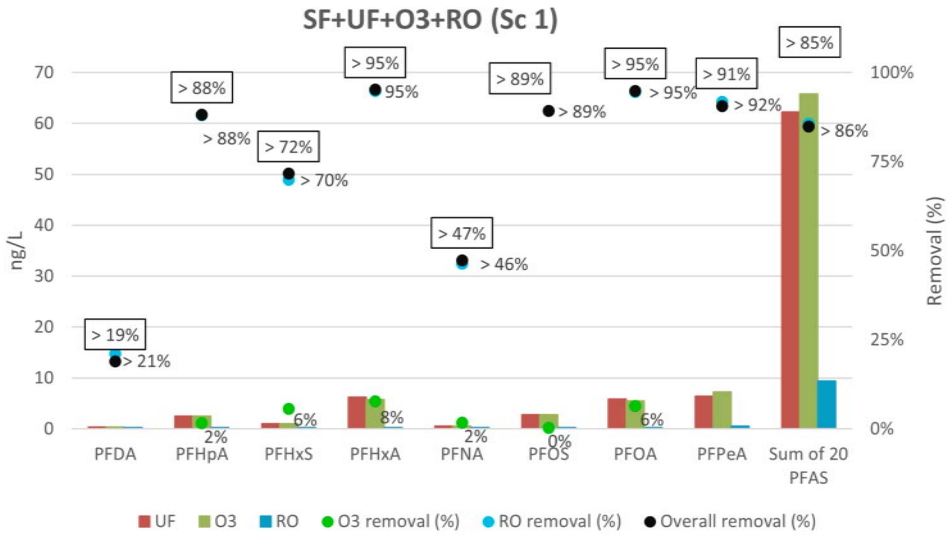

Fig. 4. PFAS concentrations (bars) and removal rates (points) throughout scheme 1.

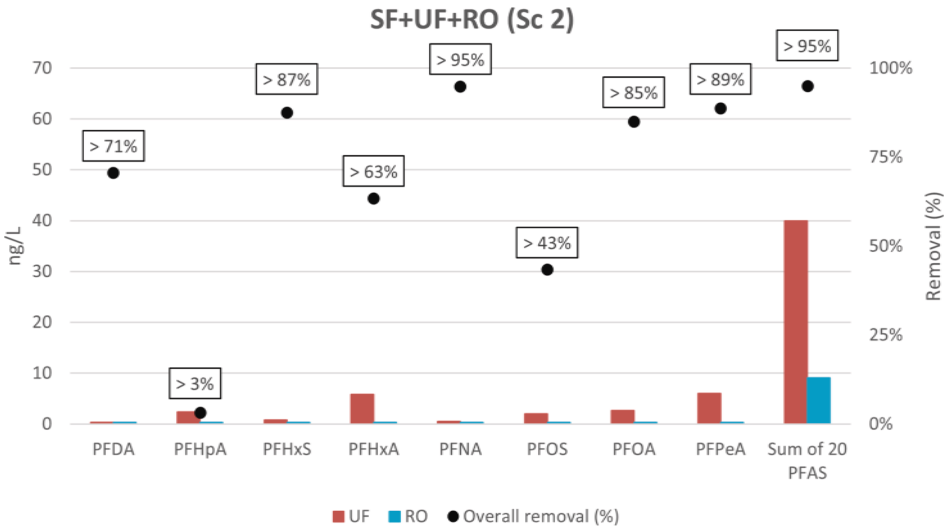

Fig. 5. PFAS concentrations (bars) and removal rates (points) throughout scheme 2.

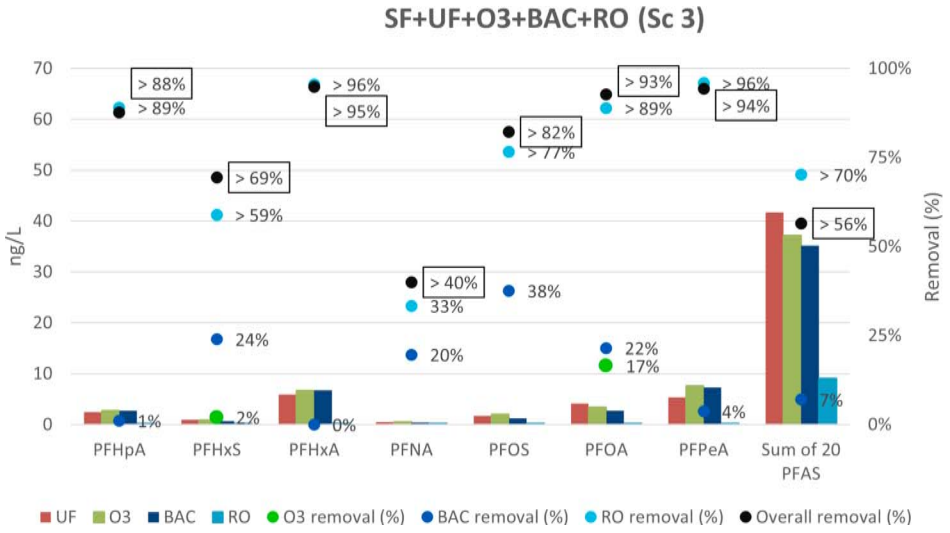

Fig. 6. PFAS concentrations (bars) and removal rates (points) throughout scheme 3.

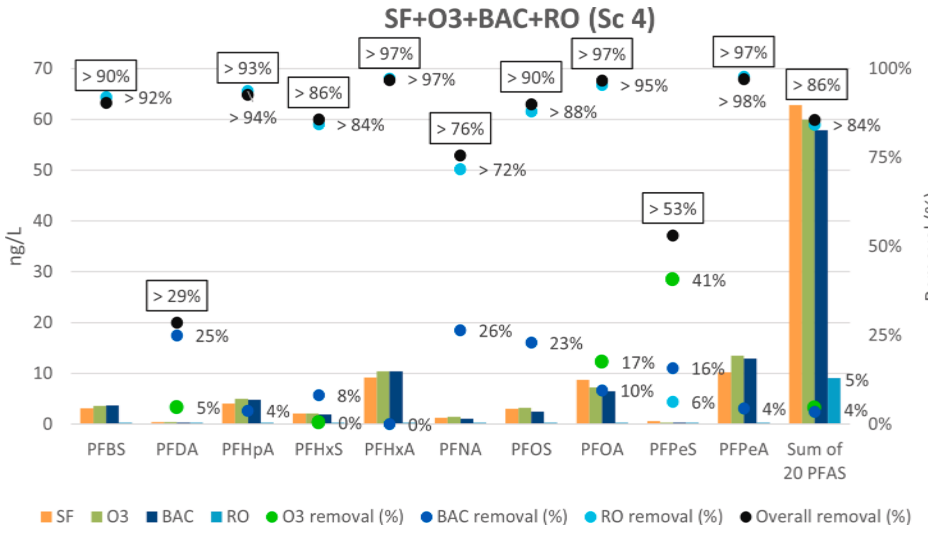

Fig. 7. PFAS concentrations (bars) and removal rates (points) throughout scheme 4.

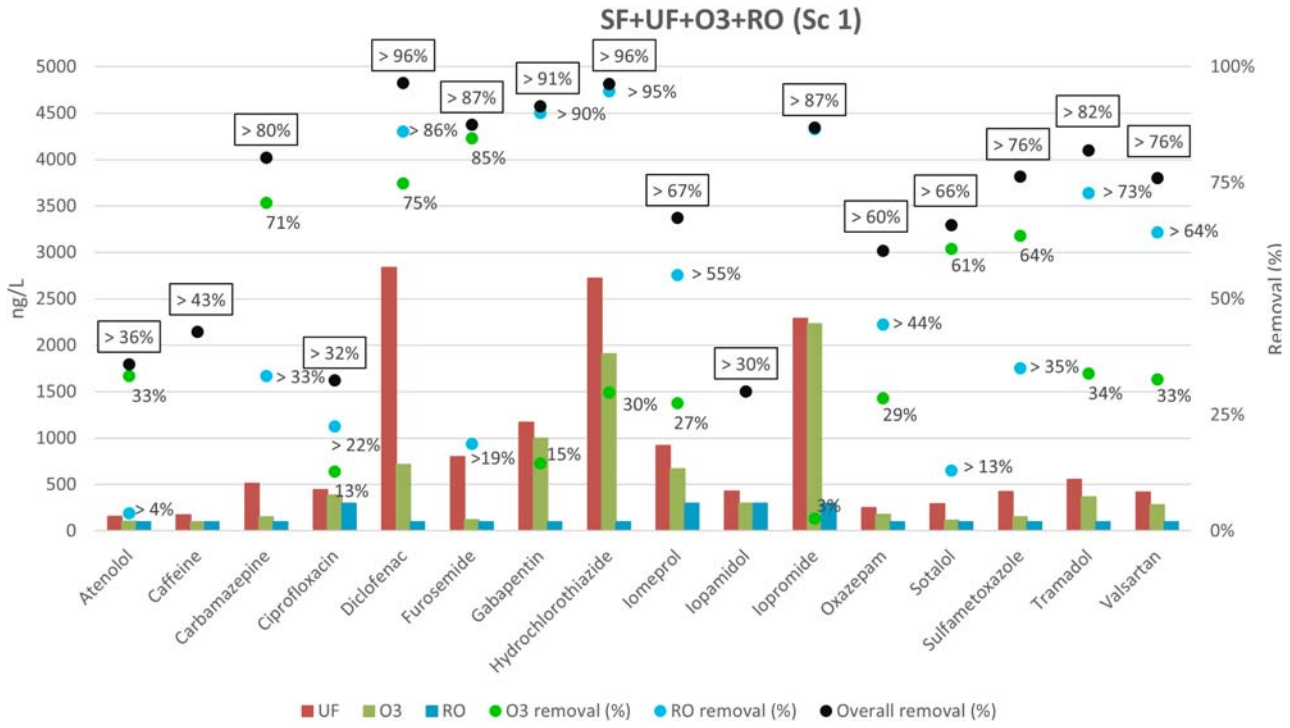

Fig. 8. PhC concentrations (bars) and removal rates (points) throughout scheme 1.

iopromide are the dominant PhCs in the influents to all potable reuse schemes. It can be observed that while the ozonation and the BAC filter contributed to the removal of some PhCs, e.g. diclofenac, gabapentin, iomeprol, and hydrochlorothiazide, the overall removal in each scheme was guaranteed by the RO system. Across all potable reuse schemes, the concentrations of all PhCs in the finished waters fare below the corresponding LOQs (commonly 0.1–0.3 μg/L; 1.2 μg/L for iopromide in scheme 2; 0.6 μg/L for ciprofloxacin and iopamidol in scheme 4). The removal rates of each potable reuse scheme and RO were limited by the LOQ values.

For the detected PhCs, ozonation showed high removal rates, achieving in schemes 3 and 4 full elimination (values below LOQ) for 16 compounds, some classified [24] of high reactivity with O_3 (e.g. carbamazepine, diclofenac, furosemide, hydrochlorothiazide), several of intermediate reactivity (e.g. ciprofloxacin, citalopram, sertraline, tramadol), and some of low reactivity (e.g. ketoprofen, oxazepan). The ones not fully eliminated were nevertheless highly removed (49 %–93 %) and included those of low reactivity with O_3 and of low-intermediate or high reactivity with hydroxyl radical (•OH) [24] (e.g. gabapentin, hydrochlorothiazide, iohexol, iomeprol, iopromide, and valsartan).

The BAC filter achieved removals of the PhCs that were not eliminated (to below LOQ) by ozone, except for iohexol in scheme 4, comprising neutral compounds (gabapentin, hydrochlorothiazide, iohexol, iomeprol, iopromide) and the anionic yet hydrophobic valsartan. Iohexol is an anionic hydrophilic compound, thus less amenable to adsorption [25–29]. Nevertheless, globally, the removals were fairly in the range of PFAS, ranging from 2 to 32 %, thus falling short of the expected [30], probably also owing to the low EBCT used in our study.

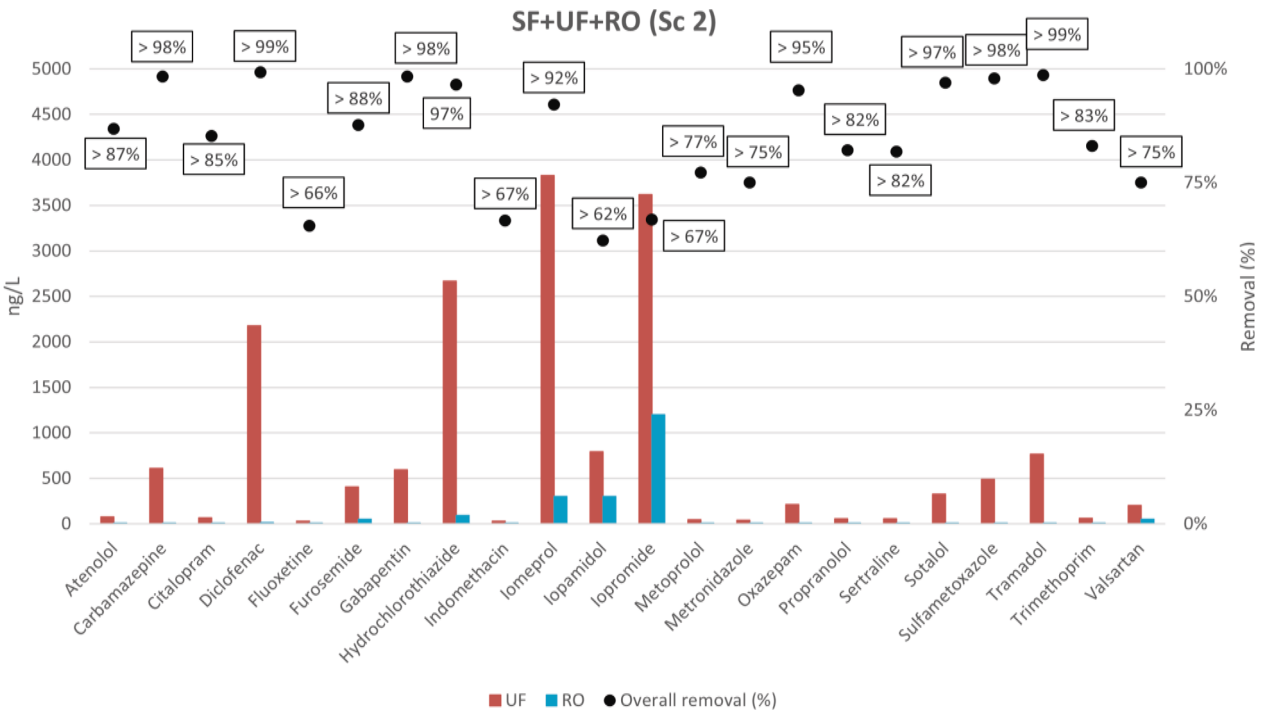

Fig. 9. PhC concentrations (bars) and removal rates (points) throughout scheme 2.

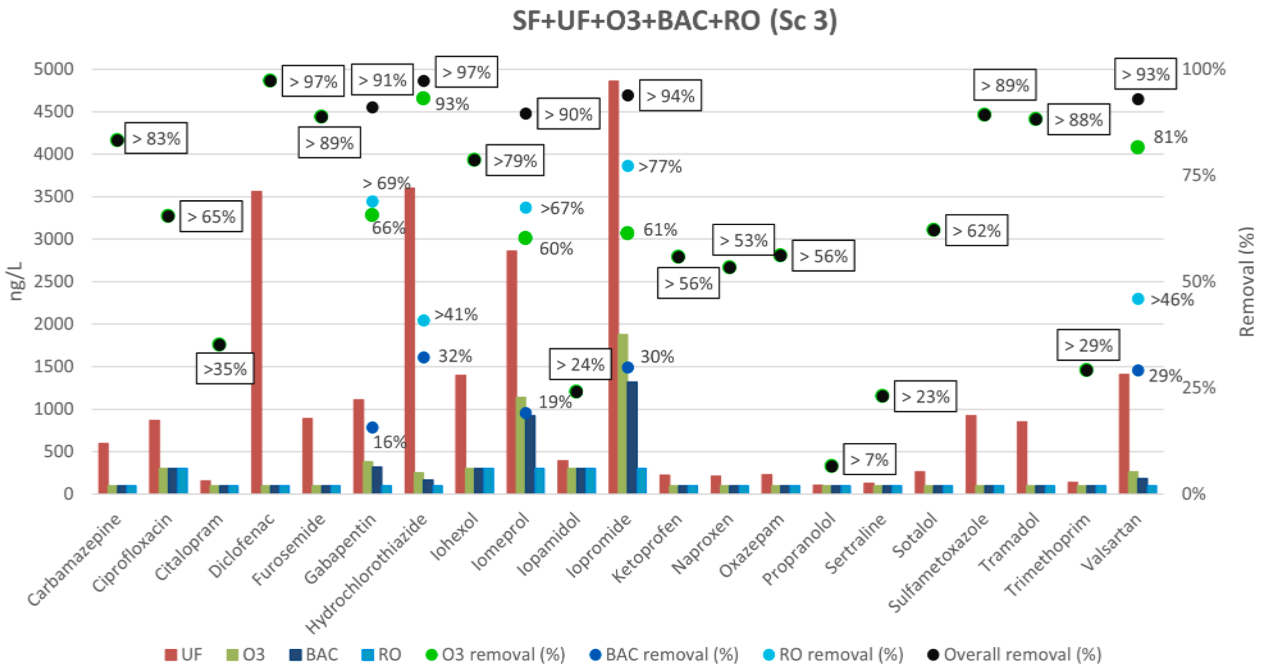

Fig. 10. PhC concentrations (bars) and removal rates (points) throughout scheme 3.

3.2.3. *Estrogenic hormones and alkylphenols*

The estrogenic hormones 17-β-estradiol and 17-α-ethinylestradiol were not detected in any of the schemes – the LOQ was 0.100 μg/L for the first three schemes and 0.050 μg/L for scheme 4. The same occurred to alkylphenols, which were not detected throughout the demonstration, with LOQ values varying from 0.010 μg/L to 0.100 μg/L, depending on the compound.

3.2.4. *N-Nitrosodimethylamine*

Fig. 12 shows the concentration of NDMA across the four potable reuse schemes. Despite the increase in NDMA concentration observed in the schemes using ozonation (negative removal efficiencies in Fig. 12), consistent with findings from other studies [30,31], all concentration values recorded (<8.4 ng/L) remained below the thresholds of 100 ng/L in drinking water [15] and 10 ng/L in potable reuse guidelines [16]. The maximum NDMA removal rate by RO varied between 29 % in scheme 1 to approximately 50 % in schemes 2 and 3. No values are available for scheme 4 due to sample damage during transportation. These results are in full agreement with other studies [32,33].

Unlike reported in other studies [30,34], the BAC filter in scheme 3

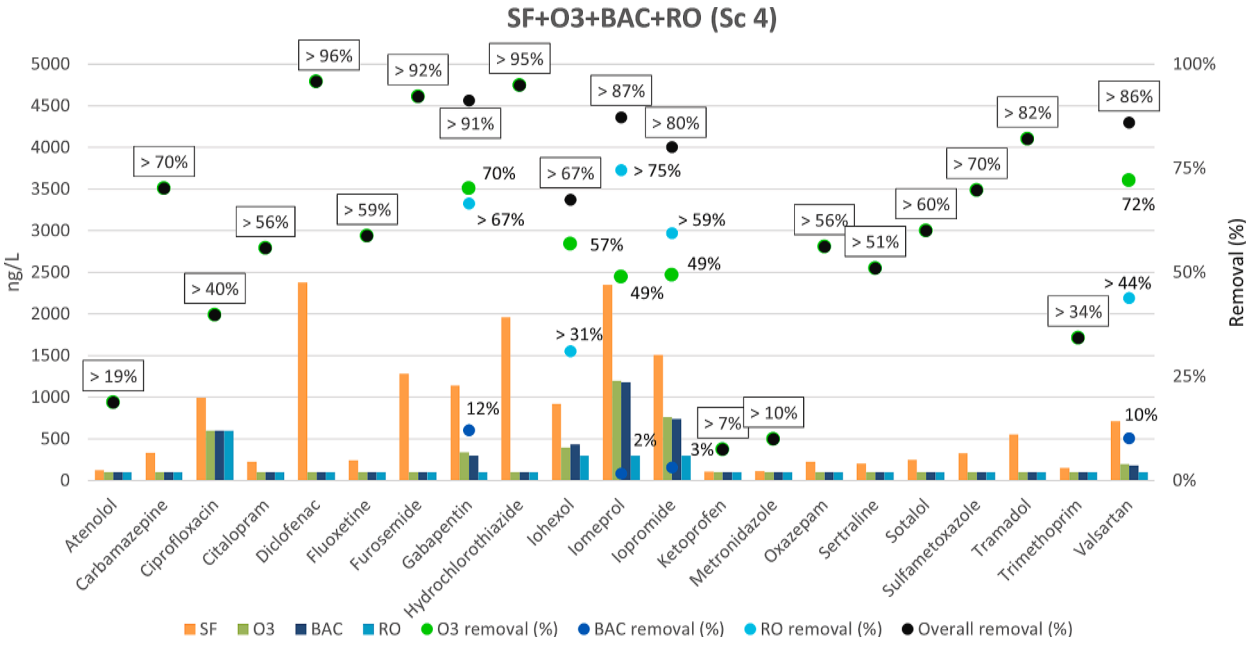

Fig. 11. PhC concentrations (bars) and removal rates (points) throughout scheme 4.

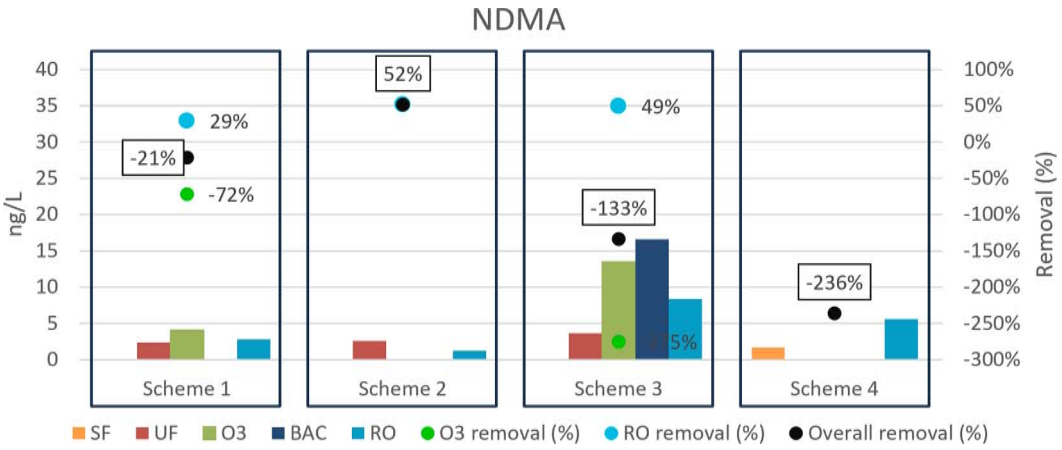

Fig. 12. NDMA concentration (bars) and removal rates (points) throughout the potable reuse schemes.

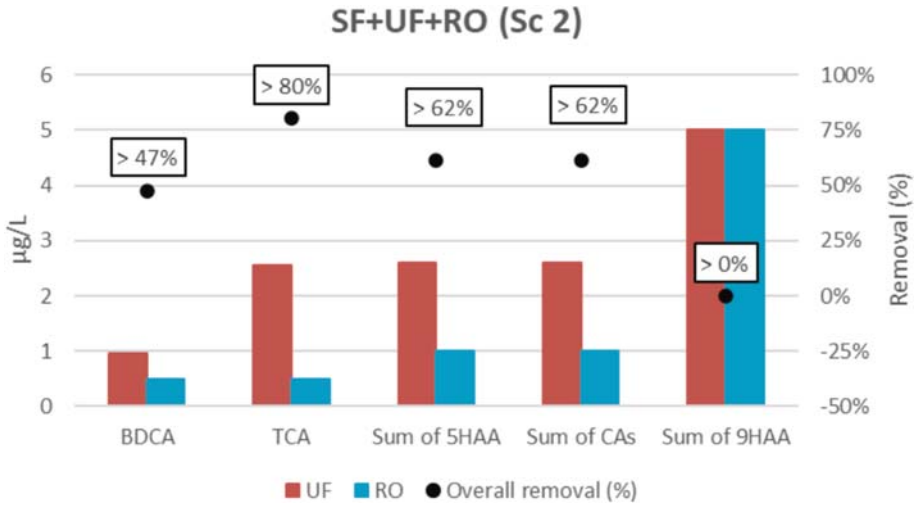

Fig. 13. HAA concentrations (bars) and removal rates (points) throughout scheme 2.

showed no NDMA removal, which was probably due to the short EBCT of 5 min.

3.2.5. Disinfection by-products

The regulated DBPs include THM total, bromate, chlorate, chlorite, and haloacetic acids. THM total varied between < 0.5 μg/L (LOQ) and 1.8 μg/L, and bromate (< 3 μg/L), chlorate (< 8 μg/L) and chlorite (< 5 μg/L) were always below LOQ.

Regarding HAAs, Fig. 13 shows the concentration detected in scheme 2. The 9 HAAs were not detected in scheme 3 and not analysed in scheme 1. In scheme 4, dibromoacetic (DBA), monobromoacetic (MBA) and trichloroacetic (TCA) acids were detected after ozonation, with concentrations below 1.7 μg/L, but not after RO, as expected [35]. Nine HAAs were analysed and their concentrations in the finished waters from all schemes were below the LOQ values, 0.5–5 μg/L for each HAA or 1 μg/L for the 5 HAAs total in schemes 2 and 4, and below the LOQs of 5–50 μg/L for each HAA or 10 μg/L for the 5 HAAs total, in scheme 3, and in all cases below the European DWD 2020 parametric value of 60 μg/L for the 5 HAAs total.

3.2.6. Organic matter parameters

DOC, TOC, A254, and A436 were analysed. Regarding the finished waters (after RO), the DOC and TOC values ranged from 0.06 to 0.46 mg C/L, thus below the DPR California requirement of TOC < 0.5 mg/L [36], the A254 ranged from < 0.0001 (LOQ) to 0.016 cm^{-1} and A436 ranged from <0.0001 (LOQ) to 0.010 cm^{-1} (Table S.8).

While ozone did not promote removals of DOC or TOC through mineralization, as expected [37], BAC attained moderate removals, 1–24 % in scheme 3 (average 9 %) and 10–17 % in scheme 4 (average 13 %), though somehow lower than expected [37–39]. RO achieved average removals of 92 %, 95 %, 94 %, and 98 %, respectively for schemes 1, 2, 3, and 4, consistent with published data [40], and the overall removals were 93 %, 96 %, 95 %, and 98 %.

Ozonation achieved an average A254 removal of 29 %, while BAC achieved an average of 12 %. RO and the overall removal were 99 %. A436, a colour indicator, was mostly removed to its LOQ (0.0001 cm^{-1}) by RO.

3.2.7. pH and electrical conductivity

As expected, neither pH nor electrical conductivity significantly changed with ozone or BAC (Table S.4 to Table S.7). Regarding pH, the average values before RO ranged from 6.6 to 7.3. After RO, as salts were removed, the average pH values were between 4.8 and 5.3.

Regarding electrical conductivity, the values ranged from 0.49 mS/cm to 3.8 mS/cm, with higher values corresponding to salt intrusion events in the sewage network, reaching the WRRF, as explained in section 2.1. With RO, an average rejection (based on the normalised salt rejection) of 99.2 % was observed, with values ranging from 98.5 % to 99.7 %, which may be apparently perceived as below the projected by the manufacturer, i.e. 99.5 %–99.7 % for a NaCl solution of 1500 ppm. However, a more detailed analysis shows an exponential decrease of the salt permeability with the salt feed concentration and conductivity rejections of 99.4 %–99.7 % in the 2500–3000 μS/cm range (corresponding to 1500 ppm NaCl), values that are fully aligned with those projected by the membrane manufacturer.

3.3. Toxicity

To assess water toxicity over the treatment schemes, water samples from different sampling points were analysed regarding *Daphnia magna* mobility inhibition and *Vibrio fisheri* bioluminescence inhibition. These bioassays enable the detection of water toxicity even at very low pollutants' concentrations (ng/L) [41]. Almost all water samples revealed very low toxicity to *Daphnia magna* and *Vibrio fisheri*, with mobility or bioluminescence inhibition, respectively, below 20 % (except in the UF treated water of scheme 3, where 30 % of *Vibrio fisheri* bioluminescence inhibition was observed), as shown in Fig. 14. Moreover, the toxicity decreased or did not change significantly with the increasing barriers in all treatment schemes, except in the ozonated water in scheme 3, where *Daphnia magna* mobility inhibition increased (13 percentual units, compared with the control), as described by other authors [42,43]. Nevertheless, *Daphnia magna* immobilization in the treated water was not detected, suggesting an improvement on water quality regarding toxicity by the RO treatment.

3.4. Operational results

During the demonstration, the operational monitoring of the pilot unit included several parameters and indicators, and the key results are herein presented and discussed. The RO feed pressure and feed electrical conductivity throughout the demonstration are depicted in Fig. 15. This figure illustrates fluctuations in feed pressure from 7 to 15 bar associated to variations in feed electrical conductivity (i.e. in the osmotic pressure), as peaks in electrical conductivity, due to salt intrusion in the sewage network, reflected in increased RO feed pressure.

The Net Driving Pressure (NDP) is the effective pressure used to permeate the water in the RO system (i.e., the difference between the feed pressure and the osmotic pressure). Fig. 16 presents the NDP results found during the demonstration, which varied between 5 and 13 bar. It indicates that scheme 2 had the lowest energy demand to operate, particularly at 60 % WRR. The occurrences of increased pressure were mainly associated with biofouling issues, which were addressed through flushing and CIP procedures. This seems to indicate an overall negative effect of ozonation on RO productivity, i.e. the potential advantage of the oxidation of the membrane foulants by ozone does not balance the increase in the water background organics' biodegradability, promoting biofilm development, as found by others [44]. BAC was introduced in scheme 3 exactly aiming at reducing the assimilable organics and therefore the biofilm growth downstream, but it failed to do so, for the EBCT was too short [30] (it was not possible to get on time a bigger filter). Membrane ageing is another effect likely responsible for the increased NDP in the latter stages of the pilot demonstration.

During the demonstration, alkaline and/or acid CIPs were performed between treatment schemes and whenever the target operational performance indicators, referred in Section 2.4.2, were exceeded.

The DPR schemes are further compared in Section 3.6.

3.4.1. Energy requirements

Twelve photovoltaic panels (2094 mm × 1038 mm × 35 mm each) with a total installed capacity of 5.4 kWp were installed on the roof of the 3.2 m × 4 m cork-coated container that harboured the RO pilot.

The data of the energy production of the panels and of the energy consumption of the pilot was available during May 2023, when the pilot was operating under scheme 1. During this period, the pilot produced 930 m^3 of water and had a total energy consumption by O_3 + RO of 1612 kWh, corresponding to 1.7 kWh/m^3 (and to 0.18 €/m^3, considering the cost of energy of the wastewater utility), with the RO pressurization being responsible for 0.8 kWh/m^3 (0.08 €/m^3), as predicted by the manufacturer's software. Simultaneously, the photovoltaic panels produced 939 kWh, which were mostly consumed by the pilot (94 %), being the remainder injected in the power grid. As such, globally, the pilot attained an energy self-sufficiency of 58 %, corresponding to 1.0 kWh/m^3. The remaining 0.2 kWh/m^3 covers the UF consumption [45]. These pilot results indicate that (if ozone is not used, as in scheme 2) a fully solar-powered UF + RO for DPR is feasible [46]. This increases the applicability of scheme 2 for decentralized, off-grid systems, as in emergency situations and in remote locations.

3.5. Water quality towards beer production

Regarding the parameters of the DWD 2020, the waters from all schemes analysed were compliant, except for pH. As salts were removed

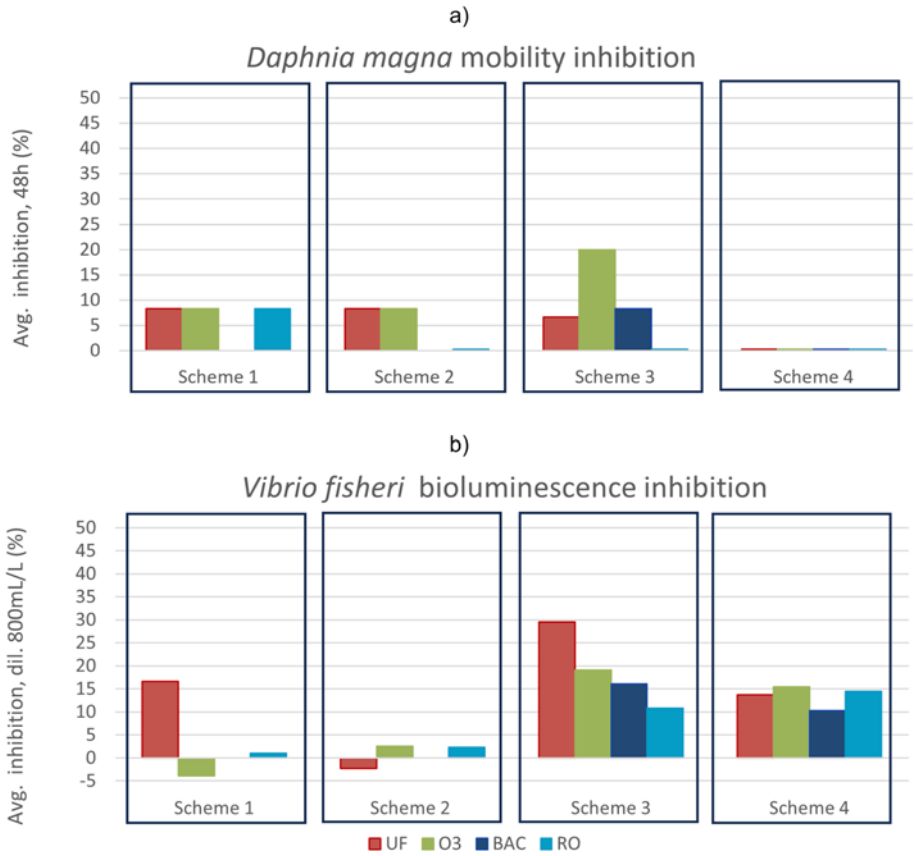

Fig. 14. Toxicity results throughout the potable reuse schemes (a) *Daphnia magna* inhibition and b) *Vibrio fisheri* inhibition).

by RO, the pH values of the permeate were below 6, whereas the parametric range is between 6.5 and 9.5. Nevertheless, calcium and magnesium salts could be added to condition the water to reduce any possible negative health impact, as well as to reduce the corrosiveness or aggressivity of water and to improve taste. This is adjustable by the beverage industry during the brewing process, also to adjust/control the taste of the beer.

Pathogen indicators (of enteric bacteria and viruses, and protozoa) were absent in the finished waters from all schemes.

Specifically regarding NDMA, the levels observed (<8.4 ng/L) are far below the Uaction level of 5 μg/L established by the United States Food and Drug Administration (USFDA) in malt beverages sold in the United States [47], and those of a recent report which presents concentrations ranging between 0.118 and 0.225 μg/L in beer samples from six different countries [48]. Nitrosamines in beer may result from the malt drying process as a result of a reaction between amines, which are naturally present in the barley, and a nitrosating agent, such as nitrogen oxides, which may be present in the air or may be formed during combustion of the fuel used for firing [47].

At the end of the demonstration, the finished water was made available to a craft beer company, which brewed 1000 L of a session IPA, a lighter, lower-alcohol version of a traditional India Pale Ale. Its organoleptic evaluation for colour, head (foam), aroma, flavour, mouthfeel, and finish was positive by the producer, showing no differences from other beers produced from conventional water, and pleasant to its consumers during events organized by AdTA (the wastewater utility).

3.6. Potable reuse schemes comparison

Four different processes were tested, namely, UF, ozonation, BAC filtration, and RO. In two schemes, low-dose chlorination was used downstream the UF for controlling RO biofouling. To ensure a high degree of oxidation of dissolved chemicals, particularly organics, the ozone dose was 1–2 mg O_3/mg TOC in the water. The BAC filter was then used for uptaking/degrading the oxidized dissolved chemicals remaining in the water, since ozonation does not ensure a complete oxidation/mineralization. However, due to equipment limitations, it was operated with an empty bed contact time of ca. 5 min, below the recommended values of 15–30 min to achieve higher removals [30].

The RO system was operated at 70 % WRR and at 60 % WRR, and the latter showed better operational results (Table 5). 60 % WRR corresponded to a permeate flowrate of 1 m^3/h and a recirculation flowrate of 0.7 m^3/h. An antiscalant (Genesys LF, AUXIAQUA) was added at 3 mg/L (dose recommended by the manufacturer) to prevent the deposit of inorganic components on the RO membranes, thus decreasing the maintenance needs.

During the pilot unit commissioning, biofilm growth in the pipes was observed. To obviate this issue, it was necessary to introduce a pre-treatment (additional barrier), chlorination, to limit the biofilm growth. Nevertheless, it was not possible to fully recover the net permeate flux, and this could have limited the WRR values achieved.

A comparison of the main analytical and operational results of the four potable reuse schemes studied (illustrated in Fig. 2) is presented in Table S.8 and Table 5, respectively. In some cases, the values of LOQ varied from one treatment scheme to another due to limitations of the lab to which the analyses were contracted.

The analytical results obtained showed no advantage in using ozonation (scheme 1) or ozonation + GAC/BAC (scheme 3) in addition to UF (+ Cl_2) + RO (scheme 2). In fact, as stressed in Section 3.2, the ozonation in schemes 1 and 3 promoted the formation of NDMA [49], which was only partly removed by the RO (≤50 %), although to concentrations below the thresholds of 100 ng/L, 10 ng/L, and 5 μg/L set for drinking water by WHO [15] and for potable reuse by NWRI-WRRF [16]

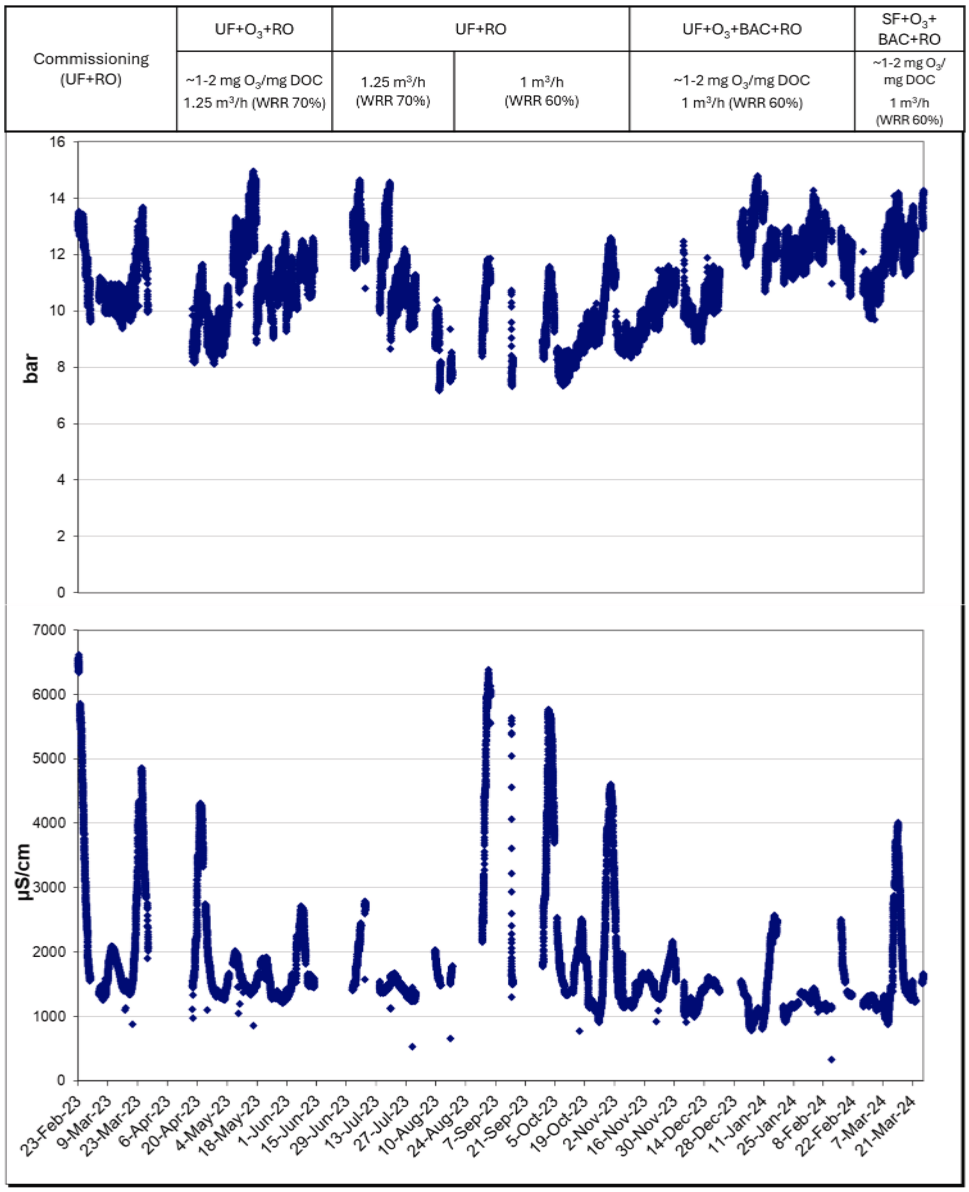

Fig. 15. RO feed pressure (above) and RO feed electrical conductivity (below) during the demonstration.

and by USFDA [47] for malt beverages, respectively.

Regarding PFAS and PhCs, as stressed in Section 3.2, all schemes allowed removal to below their LOQs. As for THMs, they were detected in schemes 2 and 4, with totals of 1.60 µg/L and 0.39 µg/L, respectively, corresponding, in scheme 2, to the presence of bromodichloromethane, chloroform, and dibromochloromethane, and, in scheme 4, to the presence of bromoform and chloroform. In scheme 2, THMs were due to chlorine dosing for biofouling control. In scheme 4, the major contributor was bromoform, which was detected at 10 µg/L after ozonation (Table S.7) and was probably formed from bromide [50], which had a higher concentration, 1.5 mg/L, in this scheme (Table S.7). No THMs were detected in scheme 3 and were not analysed in scheme 1. In all cases, THMs were always far below the DWD 2020.

Total nitrogen was also detected in all schemes, with average values of 0.5–0.6 mg N/L, which was mainly due to the presence of nitrates (Table S.7), which were nonetheless rejected by RO to their LOQ (4 mg/L). DOC average values ranged from 0.13–0.31 mg C/L, with high removals being observed by BAC (9–10 %) and mainly by RO (94–98 %).

Regarding the operational results, the parameters presented in section 3.4 and Table 5 show (i) the schemes using ozone (schemes 1, 3, and 4) involved higher NDPs, (needed for ensuring the desired constant RO flux of 21.0 or 16.8 L/(m^2.h)) and lower membrane permeability (particularly schemes 3 and 4; scheme 1 presented similar average but higher standard deviation) than scheme 2, comprising only UF (and downstream low-dose chlorination for RO biofouling control) and RO, which can be attributed to ozone by-products formation [51], (ii) a higher membrane permeability for scheme 2 operating at 60 % WRR (2.5 ± 0.2 L/(m^2h)/bar^{-1}), corresponding also to a lower NDP (7.0 ± 0.7 bar) despite the higher feed EC.

The costs involved for a 1.25 m^3/h production may be roughly estimated around 2 €/m^3 for scheme 3 and 1.5 €/m^3 for scheme 2 (not including renewable energy production in the investment costs).

4. Conclusions

Potable reuse can provide a realistic and practical source of drinking water under various circumstances, and pilot demonstration projects are essential for developing future guidelines and best practices. The work conducted in the B-WaterSmart project contributed with pilot field data to the development of such guidelines, focusing on water quality and

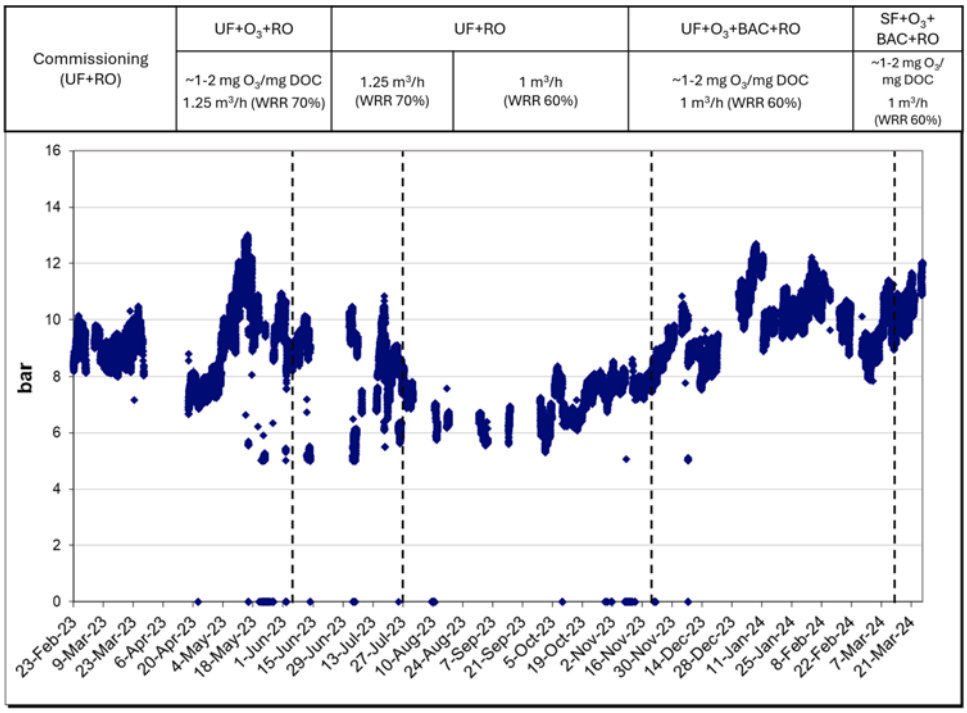

Fig. 16. RO net driving pressure during the demonstration. The dashed lines indicate the dates of the extended analytical monitoring.

Table 5
Comparison of the main RO operational results (average values and standard deviations) of the four potable reuse schemes studied.

Parameter	Scheme 1	Scheme 2		Scheme 3	Scheme 4
WRR (%)	70	70	60	60	60
RO feed temperature ± SD (°C)	23.8 ± 1.5	26.2 ± 1.3	24.6 ± 2.1	19.6 ± 1.7	18.5 ± 1.2
RO feed EC ± SD (mS/cm)	1.8 ± 0.6	1.6 ± 0.3	2.5 ± 1.4	1.4 ± 0.3	1.2 ± 0.1
RO feed pressure ± SD (bar)	11.0 ± 1.4	11.8 ± 1.3	9.6 ± 1.3	11.1 ± 1.5	11.3 ± 0.9
RO NDP ± SD (bar)	9.2 ± 1.4	8.5 ± 0.9	7.0 ± 0.7	9.5 ± 1.3	9.4 ± 0.9
RO normalised flux ± SD (L/(m^2·h))	21.9 ± 1.0	20.3 ± 0.8	17.4 ± 1.3	20.0 ± 1.1	20.7 ± 0.8
Membrane permeability ± SD (L/(m^2·h)/bar)	2.4 ± 0.4	2.4 ± 0.2	2.5 ± 0.2	2.1 ± 0.2	2.2 ± 0.1

SD: standard deviation

potable reuse schemes' operation and redundancy for the safe production, from urban wastewater, of water with adequate quality to be used in craft beer production. This involves direct potable reuse applications with additional downstream safety barriers (provided by the beer production steps).

All four multi-barrier potable reuse schemes that were pilot tested produced water of sufficient quality to be reused in the beverage industry, complying with EU and Portuguese drinking water standards. Pathogen indicators were absent. The computed LRVs of *E. coli* were limited by their low feedwater concentration and varied between >3.5 and >5.2 for UF and between 1.8 and >3.4 for ozonation, both aligned with the literature values. *Clostridium perfringens* and its spores and Somatic coliphages were fully retained by UF whereas ozonation was not fully effective. Somatic coliphages were not detected in any of the 11 samples analysed. As for trace organics, levels of PFAS, disinfection by-products, and pharmaceutical compounds were below the quantification limits (PFAS < 0.3, 0.6, 1 or 2 ng/L, 5 HAAs < 1 or 10 µg/L, bromate < 3 µg/L, chlorate < 8 µg/L, chlorite < 5 µg/L, PhCs < 0.1 to 1.2 µg/L). THMs total varied between <0.5 µg/L (LOQ) and 1.8 µg/L (far below the DWD 2020 parametric value) and NDMA was below the international guidelines for drinking water (100 ng/L) and potable reuse (10 ng/L). Overall:

- UF effectively removed microbial contaminants, ensuring water disinfection;
- Ozone effectively oxidized various inorganic and organic compounds;
- BAC filtration contributed to the removal of specific dissolved organic compounds;
- RO effectively reduced the concentration of nearly all dissolved chemicals, including oxidation by-products and recalcitrant compounds, to below their respective limits of quantification. NDMA was detected, though below international guidelines, and trace levels of THMs, DOC, and total nitrogen were also present but remained far below the parametric values set by the DWD 2020.

Operational monitoring results indicated lower normalized net driving pressure, i.e. lower energy demand, for the potable reuse scheme comprising UF (+Cl_2, whenever needed for RO biofouling control) + RO. Thus, considering the results obtained and the downstream safety barriers provided by the beer production steps (including boiling) for controlling pathogens and volatile dissolved chemicals, this scheme should be adequate for this specific application. Furthermore, the results indicate that it can be fully solar-powered. In cases where the water is to be stored, an artificial buffer (engineered storage buffer) should be foreseen and, depending on the storage time and conditions, a final chlorination may be needed to assure the microbiological stability of the reclaimed water, which would further act as an additional barrier.

At the end of the demonstration, the finished water was made available to a craft beer company, which brewed 1000 L of beer.

This study demonstrated DPR is a solution for aggravated water scarcity, localized needs and emergency situations and contributed to build societal trust in water reuse safety.

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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

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