Journal of Environmental Management 370 (2024) 122596

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Industrial circular water use practices through the application of a conceptual water efficiency framework in the process industry

Efthalia Karkou [a,*], Chuan Jiet Teo [b,c], Nikolaos Savvakis [a], Johann Poinapen [b], George Arampatzis [a]

[a] School of Production Engineering and Management, Technical University of Crete, Chania, Greece
[b] KWR Water Research Institute, Groningenhaven 7, 3430 BB, Nieuwegein, Netherlands
[c] Institute of Environmental Engineering, RWTH Aachen University, Mies-van-der-Rohe-Strasse 1, D-52074, Aachen, Germany

ARTICLE INFO

Keywords:
Wastewater treatment
Industry
Water efficiency
Circularity
Sustainability

ABSTRACT

Increased industrial water demand and resource depletion require the incorporation of sustainable and efficient water and wastewater management solutions in the industrial sector. Conventional and advanced treatment technologies, closed-water loops at different levels from an industrial process to collaborative networks among industries within the same or another sector and digital tools and services facilitate the materialization of circular water use practices. To this end, the scope of this paper is the application of the Conceptual Water Efficiency Framework (CWEF), which has been developed within the AquaSPICE project aspiring to enhance water circularity within industries in a holistic way. Four water-intensive process industries (two chemical industries, one oil refinery plant and one meat production plant) are examined, revealing its adaptability, versatility and flexibility according to the requirements of each use case. It is evident that the synergy of process, circular and digital innovations can promote sustainability, contribute to water conservation in the industry, elaborating a compact approach to be replicated from other industries.

1. Introduction

Rapid industrialization is a primary catalyst of increased freshwater demand for industrial purposes (Jain et al., 2021), resulting in natural resource depletion and wastewater generation (Kesari et al., 2021). Global climate change contributes to this situation by means of frequent droughts and rough seasonal variations (Isaac et al., 2022). In addition, the lack of reuse and recycling practices has a substantial influence (Sharma et al., 2023). It is therefore imperative to search for alternative water sources, such as rainwater (Raimondi et al., 2023), stormwater (Feng et al., 2022; Goonetilleke et al., 2017) or reclaimed water from wastewater (Liberman et al., 2020; Melián-Martel et al., 2013), and efficient management systems for industrial effluent and freshwater (Sakamoto et al., 2021).

Improvement actions with long-term impact are prerequisites for a circular economy (CE) approach in the industrial sector (Becker et al., 2019), striving for decreased use of raw materials, adoption of closed-water loops, waste minimization and prolonged value maintenance (Morseletto, 2020). Industrial wastewater treatment and management lead to valuable substances, water and energy recovery, facilitating the transition to the sustainable ‘take-make-use-reuse-recycle’ approach, with multiple economic and environmental benefits (Smol et al., 2020; Verhuelsdonk et al., 2021). Therefore, reclaimed resources and by-products are reincorporated back into the production and supply chain, aspiring to zero liquid discharge (ZLD) (Amutha, 2017; Hussain, 2020). Altman et al. (2012) studied the reuse of the cooling tower blowdown (CTBD) as make-up water after treatment by sand pack, activated carbon and cartridge filter and then nanofiltration, highlighting the potential for up to 49% wastewater discharge reduction and substantial water savings. However, scaling phenomena have to be taken into account for the system’s optimization. Rahmani (2017) increased the cycles of concentration of cooling towers from 6.5 to 9.0 and optimized the scaling and corrosion inhibitors, achieving to save water up to 1.1 million m^3/y. Davood Abadi Farahani et al. (2016) concluded that the CTBD treatment by coagulation-flocculation and reverse osmosis (RO) is the most cost-effective, efficient method for removing chemical oxygen demand (COD), total dissolved solids (TDS), turbidity and conductivity, producing water suitable for reuse. In

* Corresponding author.
E-mail address: ekarkou@tuc.gr (E. Karkou).

https://doi.org/10.1016/j.jenvman.2024.122596
Received 20 March 2024; Received in revised form 20 August 2024; Accepted 17 September 2024
Available online 24 September 2024

addition, the treatment of cooling water by membrane distillation utilizing waste heat for the production of boiler feed water (BFW) proved efficient, requiring even 2.25 kWh/m^3 less energy and causing 50–75% lower CO_2 emissions compared to other technologies. However, pre- and post-treatment processes may be required (Kuipers et al., 2014). Müller et al. (2024) reported that CTBD treatment has to encompass biological activated carbon (BGAC), ultrafiltration (UF) and RO to produce suitable make-up water for reuse in terms of total organic carbon (TOC) and conductivity. Sandoval et al. (2024) treated wine slaughterhouse wastewater by electrocoagulation, optimizing the current density and supporting electrolyte, and achieved a reduction of up to 72.7% of TOC, 89.4% of COD, 72.3% of total nitrogen (TN), 96.3% of total phosphorus (TP) and complete disinfection. However, the prospect of energy-efficient technologies emerged.

It is a common practice to discharge effluents into the environment while ensuring environmental protection. However, reclaimed water has the potential to be exploited as firefighting water, drinking water, for cooling purposes, such as in cooling towers (CTs) and heat exchangers or for steam production and aquifer recharge (Guven et al., 2023; Kesari et al., 2021; Misrol et al., 2021). Thus, treatment technologies have been studied in the tannery (Ricky et al., 2022), petrochemical industry (Sakamoto et al., 2021) and brewery along with green practices, considering technological and economic criteria (Ashraf et al., 2021). Full-scale wastewater treatment plants (WWTPs) were monitored to quantify CH_4 and N_2O emissions and determine the most impactful technologies, concluding that secondary biological treatment accounted for 97.0% of CH_4 and 91.0% of N_2O emissions that were 447.7 and 1605.3 $kg_{CO2\text{-}eq}$/d, respectively (Q. Wang et al., 2024). Digital advancements, i.e., Internet of Things (IoT), big data, data analytics and monitoring devices have to be deployed. The monitoring and optimization of coagulation-flocculation and advanced oxidation process (AOP) in the study of GilPavas et al. (2017) led to optimal organic matter removal and enhanced process efficiency. Warren-Vega et al. (2024) developed an artificial neural network to predict and optimize the performance of AOPs when treating piggery wastewater. A process modelling and simulation framework for digital twins was developed for the industrial sector (Sarantinoudis et al., 2023). Glatt et al. (2021) implemented a digital twin in the manufacturing sector for system monitoring, predicting and failures diagnosing. In addition, stakeholders' involvement is necessary (Bressanelli et al., 2020; Mhatre et al., 2021).

The research for water/wastewater treatment technologies selection (Büyüközkan and Tüfekçi, 2021; Quaglia et al., 2014), water quality monitoring (da Luz et al., 2022), performance indicators (Foglia et al., 2023; Preisner et al., 2022), circular practices (Arora et al., 2022) and digital innovations and cyber-physical systems (Azzaro-Pantel et al., 2022; Juneidi et al., 2022; Matheri et al., 2022; Pham et al., 2016; Radini et al., 2021) in the industry, under technological, economic, and environmental criteria (Lizot et al., 2021; Tsui et al., 2022; Walsh et al., 2016) is intense, but discrete. To authors' knowledge, the synergistic impact of such advanced innovations has not been studied for the industrial sector. In the context of the AquaSPICE "Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations", which is an EU-funded project under H2020, a comprehensive CWEF was developed to support and provide an in-depth understanding of holistic decisions for water use in industry. The project aims to materialize circular industrial-scale water use practices, demonstrating innovative solutions through advanced technologies, fit-for-purpose closed-loop practices and water cyber-physical systems at different levels.

There is lack of research in consolidating and actualizing a framework related to water/wastewater treatment methods, water circularity practices and digital tools/services in the industrial sector. Wastewater treatment system configuration selection is a challenge since multiple barriers have to be overcome, with legal requirements and volume to be the most critical ones according to (Trianni et al., 2021). The industrial water mass balance deployed by Pham et al. (2016), as a water management tool, showed the necessity of data availability and performance indicators use. Machine learning methods were applied in the study of Bellamoli et al. (2023), performing binary and multiclass classification, to detect and classify the main anomalies successfully. However, model precision can be further enhanced. By coupling technological and digital innovations in the water sector, around 3.6% cost reduction, 4.1% revenue increase and 15% less CO_2 emissions globally are projected (Kurniawan et al., 2023). Our paper fills this gap by bringing the novelty of (i) holistic, integrated and flexible solutions to deploy water use practices within the process industry by combining process innovations, circular practices and digital tools/services in view of technology, environment and economy and (ii) their fit-for-purpose actualization in different real case studies.

In this regard, the CWEF is applied to four water-intensive process industries, i.e., two chemical industries, an oil refinery and a meat production plant, to illustrate its adaptability depending on case-focused requirements. Hence, this study will enable replication in other process industries, contribute to the decision-making by stakeholders and industrial partners for water/wastewater technologies selection, fit-for-purpose reuse and recycling practices and digital innovations that can be deployed depending on the industrial case's peculiarities. Ultimately, the outcome of the study gives valuable insights and recommendations to the scientific community on enhancing water circularity within the process industry.

2. Methodology

To reuse reclaimed water for industrial purposes, it must comply with the intended reuse quality requirements (The European Parliament and the Council, 2020). However, conventional wastewater treatment may be insufficient for achieving this goal (Helmecke et al., 2020). On the contrary, advanced treatment technologies, circular actions (water recirculation and exchange and synergies among different actors), as well as real-time control and monitoring systems offer significant impetus for reaching sustainability goals (Kamble et al., 2018). Therefore, it is evident that the coalescence of these three aspects is indispensable. To deliver compact water-related industrial solutions, the CWEF was described in detail elsewhere (Teo and Poinapen, 2021). The fundamental pillars are process innovation, circular practices and digital tools. Fig. 1 presents the circular industry-oriented framework, which aims to facilitate the implementation of sustainable water use practices and optimize resource management, enhancing water circularity and efficiency in the industry. It consists of four consecutive phases, following a 10-step methodological approach as described below.

Phase 1: Evaluation of the current situation and definition of targets (3 steps)
Phase 2: Inventorization and investigation of the main pillars (1 step)
Phase 3: Assessment and expected output (3 steps)
Phase 4: Business model, policy development and dissemination activity (3 steps)

The first phase, *evaluation of the current situation and definition of targets*, highlights the objectives (step 1) for the framework application, which should be clearly outlined to support complex issues that arise within a plant, e.g., reduce freshwater consumption, increase reuse and recycling practices, upgrade the processes or promote digitalization. The scope is important in order to assess progress and focus on the defined goals. In addition, the definition of the user requirements and a baseline assessment (step 2) follow, by identifying the participating actors (process industries, public or private companies, municipality, etc.) and collecting data regarding a specific case through personal interviews, questionnaires or workshops. Therefore, initial screening (step 3) is carried out in relation to the existing ICT infrastructure, current water and wastewater treatment technologies, quality of raw water and

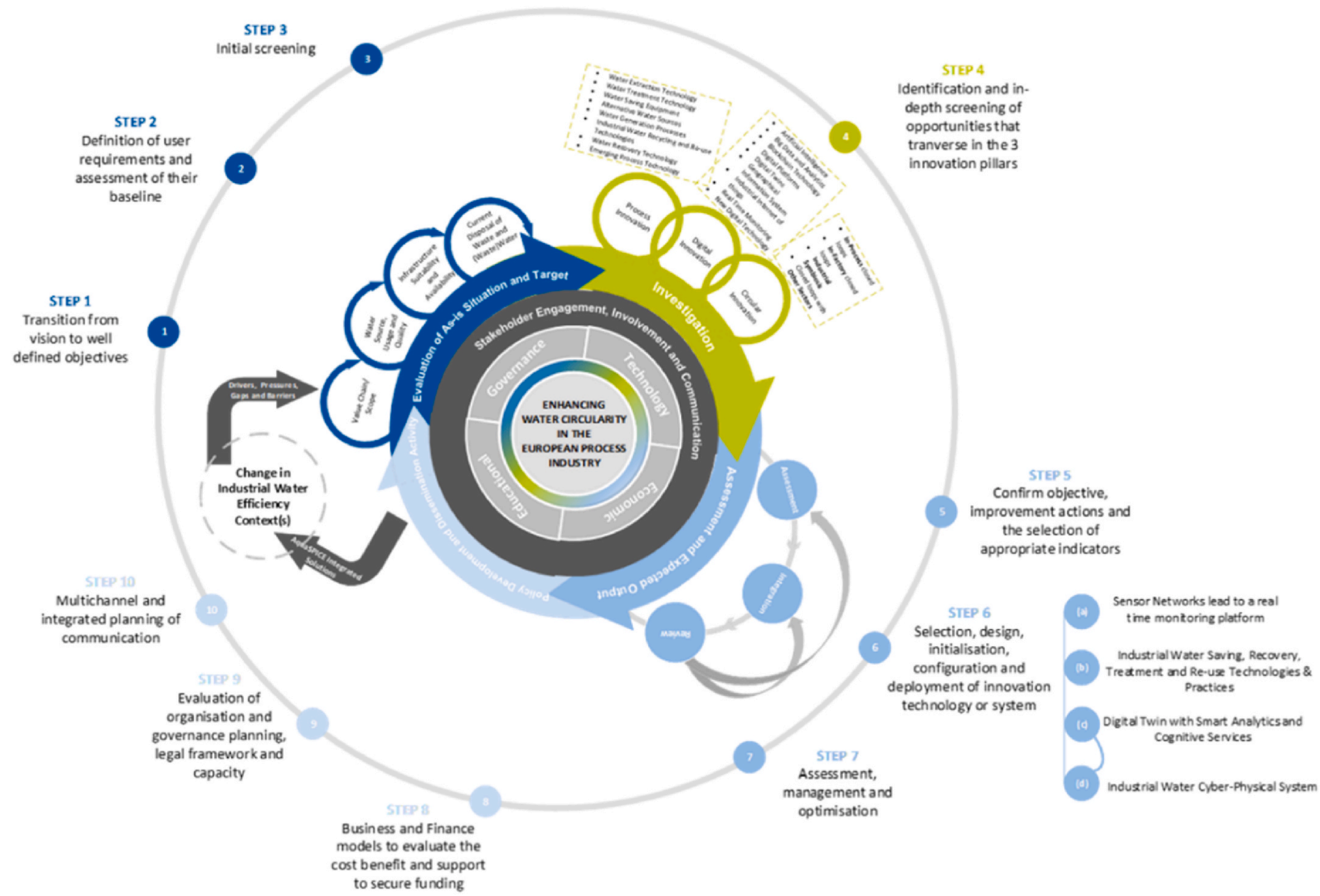

Fig. 1. The conceptual water efficiency framework (Teo and Poinapen, 2021).

wastewater, wastewater specifications, and local permits.

The second phase, *inventorization and investigation*, explores and identifies the options for water and wastewater treatment and management along with potential improvements. The main pillars of innovation (process, circular and digital) are thoroughly examined (step 4). Process innovations refer to the abstraction, treatment, saving, reuse, recycling and recovery of water. In addition, alternative water sources, advanced processes and water generation technologies are inventorized and investigated. Their imminent implementation should fulfil the user's needs. Furthermore, a circular approach promotes a sustainable and efficient resource management in the industry at different levels. The technologies allow the efficient water management and adoption of closed-loop practices, e.g., through treated industrial effluents' reuse. To this end, modelling the deployed system is needed, the boundaries of which can be either narrow (e.g., a processing unit, the whole factory) or extended (e.g., multiple process industries/actors). Modelling tools predict the processes' performance, estimating water quality and quantity, chemicals consumption and energy requirements. Overall, four modelling levels are identified (Fig. 2-A). In-process modelling is applied through the development of mathematical models. Water management across a wider system is modelled by formulating water balances, including input, output, and water loss (in-factory modelling). In case a process industry cooperates with others of the same sector via materials exchange, industrial symbiosis models are applied. The most wide-ranging level, systemic modelling, concerns the closing of water loops among industries, businesses, or public authorities through intra-factory reuse (Karkou et al., 2022).

In addition, digital innovation allows the interconnection of physical-digital systems, facilitates data collection and analysis and contributes to continuous monitoring and dynamic controlling of the industrial systems. The representation of the physical by a digital system is called digital twin (Maddikunta et al., 2022). In this regard, a real-time monitoring (RTM) platform provides data for modelling and simulation activities and data analysis (Okorie et al., 2018; Sarantinoudis et al., 2023). Descriptive and predictive analytics indicate the trend for deviation of target parameters in a predefined pattern and predict their behaviour, respectively. The user performs data mining techniques for data analysis to identify any intrusion (Deshpande et al., 2019). Virtual sensors, or else soft sensors, are innovative digital tools used to extract data from different data sources, in case physical online sensors fail to operate. However, their usage should be temporal (Ilyas et al., 2020). Therefore, these digital tools open the path for optimization services to enhance the performance of processes and recirculating cooling water systems in the industry, including CTs, aiming at optimal water and energy efficiency (K. Ma et al., 2020). Improved efficiency and optimal scenario selection are key aspects for water/wastewater treatment. The digitalization of the industries is promising for decarbonizing, saving energy and protecting the environment, since the ICT sector can bring in innovative solutions (Kurniawan et al., 2023; R. Ma et al., 2023).

Previous researchers have developed an optimization model to minimize freshwater intake and wastewater production, defining constraints and reuse options (Nemati-Amirkolaii et al., 2021). By monitoring a set of indicators, dynamic life cycle assessment (LCA) is feasible, evaluating and quantifying the environmental impact and allowing the comparison of alternative scenarios (Azzaro-Pantel et al., 2022). Hence, LCA contributes to the decision-making process in industry (Mehmeti et al., 2018; Yang et al., 2020). These services can be integrated into a

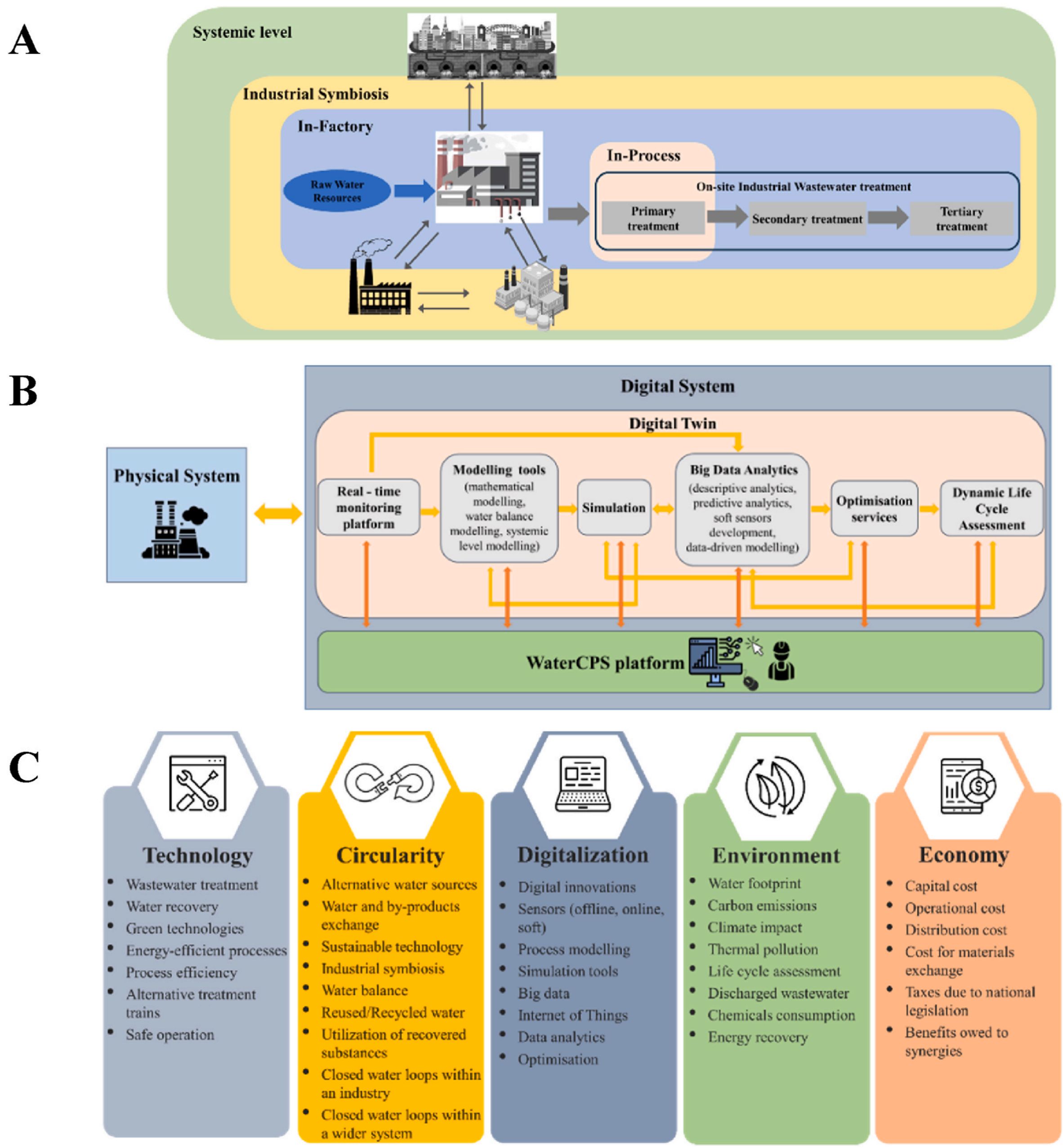

Fig. 2. Different modelling levels in the industrial sector (A), digital innovations overview (interconnection between the physical and the digital system) (B), and relevant aspects of industrial water and wastewater management (C).

water-related Cyber-Physical System (WaterCPS) platform, a unique and innovative digital tool. Any action that leads to overexploitation of natural resources and higher expenses must be ruled out. Fig. 2-B reveals the interdependencies of the individual innovative digital tools that constitute the WaterCPS platform.

Regarding the third phase, *assessment and expected output*, the most proper improvement actions are selected, implemented and evaluated through relevant performance indicators (step 5). Treatment technologies are selected, designed, and deployed (step 6), exploiting the three innovation pillars. Therefore, the integrated system is assessed and optimized (step 7). Finally, the fourth phase, *business model, policy development and dissemination activities*, should apply to all industries that aspire to enhance water circularity and implement innovative solutions. It encompasses the development of business and finance models (step 8) to conduct cost-benefit analysis and search for potential sources of funding. Additionally, governance planning and legal framework are evaluated based on the location of the process industry (step 9). As the last step, multichannel and integrated planning of communication activities occur, since knowledge diffusion and networking are crucial (step 10).

To evaluate the impact of such interventions within the industrial boundaries, technological, economic, and environmental aspects are included. Fig. 2-C highlights the topics which must be investigated for each aspect (Technology, Circularity, Digitalization, Environment and Economy). To provide an in-depth understanding of this versatile framework, it is applied to 4 process industries, studied in the course of AquaSPICE H2020 innovation actions, aiming to materialize and enhance water efficiency, highlighting potential barriers, gaps, and challenges.

To apply the CWEF to the case studies, it is worth mentioning that process-, circular- and digital-focused industrial practices in different types of factories have been applied, including the measured quality parameters, the influencing parameters, implemented digital services and the main findings of each study, which will point out the existing industrial practices and set the baseline for going far beyond the results described in Table A1 (Appendix). As is evident, many researchers attempted to close the water loops or take measures for environmental protection through water and wastewater treatment processes along with the implementation of specific digital services. Despite the ambitious outcomes of the synergistic implementation of all innovations, none has investigated their impact in real case studies in the industrial sector.

2.1. Case studies description: resource of water

2.1.1. Chemical industry 1

Chemical industry 1 supplies specialty chemicals, advanced materials and plastics. Water management is challenging due to the limited natural resources in the coastal area of the Netherlands, where the industry is located. The goals encompass the reduction of freshwater consumption by 2.25 million m^3/y and discharged wastewater by closing the water loops, reusing and recycling the industrial effluents, such as CTBD and slightly polluted streams. Smart monitoring and other digital solutions' deployment are intended.

2.1.2. Chemical industry 2

Chemical industry 2 is located in Germany and produces a variety of products, including chemicals, advanced materials and plastics, by consuming vast amounts of water. Industrial activities, among others, lead to freshwater resources reduction and the area becomes water-stressed. Hence, it is essential to investigate alternative water sources or manage water resources efficiently. The reduction of abstracted freshwater through optimization, wastewater treatment with fit-for-purpose technologies, reuse and recycling are the goals. In addition, smart monitoring aims to create a water management system to control raw water abstraction, wastewater discharge, and recycling streams.

2.1.3. Oil refinery plant

The water-intensive oil refinery plant is located in Turkey. Freshwater is abstracted from a nearby lake to process approximately 30 million tons of crude oil annually. The plant generates immense amounts of wastewater that contains harmful and toxic contaminants. To reuse the effluents, treatment to reach the desired quality criteria, mixing optimization of treated wastewater and freshwater and the deployment of sensors and smart monitoring tools are essential. The main goals encompass freshwater reduction, water reuse increase by 50% and decrease in wastewater discharged into the environment.

2.1.4. Meat production plant

The meat production plant in Romania produces approximately 150 tons of meat products daily. It is a water-intensive industry since the production of 1 kg of meat product requires the consumption of more

Table 1
Composition of freshwater and industrial wastewater (raw or partially treated with WWTP) of the process industries.

Quality parameter	Unit	Chemical industry 1	Chemical industry 2				Oil refinery plant		Meat production plant
		CTBD	Lake	River	CTBD	Conden-sate	Stream 1	Stream 2	Wastewater
pH	–	–	7.39–8.12	7.74–8.20	6.82–8.47	6.43–8.89	–	>13.00	6.81–7.56
Fat, Oil and Grease	mg/L	–	–	–	–	–	–	–	93.00
TOC	mg/L	35.00–65.00	5.00–9.00	5.00–16.00	14.00–24.00	0.20–2.20	–	–	25.10
TSS	mg/L	–	2.00–126.00	2.00–147.00	–	–	10.00–60.00	–	8.00–248.00
TDS	mg/L	1766.35–2363.45[a]	91.04–347.34[a]	208.13–986.40[a]	552.14–1580.04[a]	0.017–1.65[a]	2000-6000	1031-3644[a]	1000
COD	mg/L	–	14.00–34.00	12.00–38.00	20.00–83.00	–	100–180	2200–6900	311–621.71
BOD	mg/L	–	–	–	–	–	–	–	38.00–461.00
Turbidity	NFU	–	1.00–8.40	1.00–25.50	1.00–3.90	–	–	–	43.00
Conductivity	μS/cm	2500–4000	466–690	571–1415	1728–2707	0.20–7.30	2500-15000	1000–52000	1888
Bicarbonate	mg/L	–	1.30–2.56	1.40–3.75	0.60–2.18	–	–	–	–
Nitrate	mg/L	50.00	0.01–84.00	1.40–5.90	3.70–21.00	–	–	–	0.77–3.48
Ammonium nitrogen	mg/L	–	–	–	–	–	2.00–8.00	11.00–83.00	–
Ammonia/ Ammonium	mg/L	–	–	–	–	–	–	–	16.10–89.10
Sulfates	mg/L	1000–1200	1.00–139.00	115–446	266–831	–	–	–	93.60–194.52
Sulphur	mg/L	–	–	–	–	–	0.50–2.00	20.00–61.00	–
Phosphate	mg/L	–	0.10–0.54	0.10–0.39	0.16–4.40	–	–	–	0.62–9.13
Phosphorus	mg/L	–	–	–	–	–	–	–	0.47–6.54
Phenol	mg/L	–	–	–	–	–	–	1000–3500	–
Sodium	mg/L	210–500	32–50	37–400	49–325	0.00–0.24	–	–	–
Potassium	mg/L	50.00	5.70–7.60	3.80–10.00	–	–	–	–	–
Calcium	mmol/L	5.00–11.25	0.80–1.80	1.30–4.00	2.80–6.30	–	–	–	–
Copper	mg/L	–	0.10	0.10–0.18	0.00–0.12	0.001–0.005	–	–	0.285
Chloride	mg/L	400–500	50–60	48–116	227–388	0.01–1.30	–	–	157.40–531.70
Iron	mg/L	0.00–0.35	0.01–1.70	0.01–0.11	0.03–0.70	0.001–0.02	–	–	–
Cadmium	mg/L	–	0.01	0.01	–	–	–	–	0.12
Zinc	mg/L	1.00–1.50	0.01–0.03	0.01–0.06	0.50–1.30	–	–	–	0.41
Manganese	mg/L	–	–	–	0.00–0.04	–	–	–	–
Magnesium	mg/L	50.00	–	–	–	–	–	–	–
Barium	mg/L	0.15	–	–	–	–	–	–	–
Aluminium	mg/L	0.20	–	–	–	–	–	–	–
Silica	mg/L	–	–	–	2.35–13.26	0.005–0.08	–	–	8.60
Total Count	CFU/ 100 mL	–	–	–	–	–	–	–	$4 \bullet 10^5$
Total Coliform	MPN/ 100 mL	–	–	–	–	–	–	–	2419

[a] TDS was assumed as the sum of the measured ion concentrations.

than 6 L of water. It aspires to improve water efficiency and water circularity through wastewater treatment and management, monitoring services, process optimization and internal closed-water loops. Hence, the goal is to reduce freshwater intake by 30% and incorporate a digitalized water management system.

3. Results and discussion

The CWEF is applied to two chemical industries, an oil refinery plant and a meat production plant. The following section presents, analyzes and assesses the outcomes for each individual industry collecting qualitative and quantitative data. To begin with, Table 1 summarizes the composition of the targeted water/wastewater streams for each case study.

Each process industry aims to monitor specific key quality parameters. For chemical industry 1, the main quality parameters are turbidity, TOC, conductivity, pH and the measured ions. As far as the streams of chemical industry 2, the important quality parameters include pH, COD, TOC, conductivity and several ions (calcium, magnesium, zinc, phosphorus, iron and silica). The oil refinery plant aspires to control pH, COD, conductivity, TOC, sulphur and ammonium nitrogen. The meat production plant as a food industry is concerned about BOD, COD, total suspended solids (TSS), phosphorus, nitrate and microorganisms.

The selection and deployment of process, circular and digital innovations in the individual case studies depends on specific performance indicators, as shown in Table 2. Freshwater consumption reduction, which was calculated based on the reclaimed water derived from the industrial wastewater treatment trials, reclaimed water reuse increase, system improvement, real-time monitoring and digital tools implementation consist of fundamental criteria, whose determination derives from the objectives of each industrial case study.

3.1. Chemical industry 1

3.1.1. Evaluation of the current situation and definition of targets

A drinking water company and a national park are the water suppliers. For the operation of the 16 CTs, water and air are provided and mass transfer takes place because of the vapor concentration difference between the two phases, i.e., liquid and gas, leading to volatile constituents' evaporation, air moisturizing and water temperature decrease (Ruiz et al., 2022). Currently, freshwater and treated wastewater are used as CTMU water affected by seasonal variations (up to 10–15% during summer). Each cell has a separate process control system. CTBD consists of concentrated cooling water, whose composition is shown in Table 1, and has the potential to be reused (Saha et al., 2020), e.g., as CTMU water. Approximately 1.6 million m^3/y of CTBD is generated of which one-half is discharged into the river and the other half is treated in the WWTP. Probes, including temperature and conductivity, sensors for TOC, and flow rate valves monitor critical quality parameters. All of them are installed in 45 locations and the measured data are provided to the central control system.

3.1.2. Investigation

Fig. 3-A presents the process flow diagram of the chemical site. The green and yellow frame describe the CTBD and DSPW treatment point, respectively. To expand the available opportunities in process innovations, wastewater streams should be treated with a set of selective technologies aiming for the removal of target contaminants. CTBD stream must meet the quality specifications for cooling water, as shown in Table A2 (Appendix), to be reused as CTMU. The appropriate processes to remove the excess concentration of dissolved solids comprise BGAC filtration, electrocoagulation, and membrane-based technologies. In this regard, the production of water free from macromolecules and small organic compounds, turbidity-related constituents, suspended solids and dissolved ions is feasible. Organic matter is adsorbed on BGAC's biofilm and then biodegraded (Ribeiro dos Santos et al., 2022).

If the wastewater contains recalcitrant organic pollutants, AOPs can degrade them (Sillanpää, 2020). Electrocoagulation removes suspended and dissolved matter by electric supply (Syam Babu et al., 2020). Membrane-based separation processes utilize semipermeable membranes to retain most of the salts and ions, resulting in the production of a stream enriched in water (Hankins and Singh, 2016). However, biofiltration should precede to protect the membranes (Griebe and Flemming, 1998). During the CTBD treatment, it is imperative to control the growth of *Legionella* and pH by using chemicals at adjustable dosages (Abdel-Shafy et al., 2020; Iervolino et al., 2017). The Gram-negative bacterium, called *Legionella*, is a serious contaminant in cooling water with a survival capability within the range 5.7–63 °C (Girolamini et al., 2023). Enhanced CT water efficiency is ensured through a high recirculation factor to such a point so as to avoid scaling and corrosion (Rahmani, 2017). Fig. 3-B indicates also the alternative water treatment trials for CTBD.

Optimized water efficiency is feasible through modelling, simulation activities, data analytics and optimization of the treatment technologies.

Table 2
Performance indicators for all process industries in this study.

Performance Indicator	Chemical industry 1	Chemical industry 2	Oil refinery plant	Meat production plant
Water Sustainability	10 million m^3/y of freshwater is required. Reduction of freshwater by 1.5 million m^3/y.	Around 8.2 million m^3/y of freshwater is required. Reduction of freshwater by 1.1 million m^3/y.	Around 893.000 m^3/y of wastewater is generated. Reduction of freshwater of around 1.3 million m^3/y.	396.000 m^3/y of freshwater is required. Reduction of freshwater intake by 118.800 m^3/y.
Water-Eco	CTBD reuse by 90%.	Reuse CTBD by 55% and condensate by up to 10%.	Increase reclaimed water to be reused by at least 50%.	Intra-factory reuse by 30%.
Improved water quality	Removal of TOC, turbidity, suspended solids, conductivity, and dissolved ions.	Enhance cooling tower make-up (CTMU) water quality. Improve demineralized water quality in terms of TOC, conductivity, and silica.	Removal of TOC and turbidity.	Water quality in accordance with EU requirements and national legislation.
Financial efficiency	–	–	–	Potential economic benefits due to by-products supply to another industry.
Digital upgrade	Real-time monitoring. Digital tools deployment.			
Plant operation	–	Low corrosion rate, scaling, and biofouling. 8 years without turnaround.	Maintain quality of discharged wastewater within the acceptable limits by 90% of the year.	–
Knowledge share	–	–	Act as role model for the petrochemical industry.	Serve as an exemplary food industry regarding water management.

Reduction in freshwater consumption (m^3/y) = Required freshwater by the industry (m^3/y) – Reclaimed water from industrial wastewater treatment (m^3/y) (1).

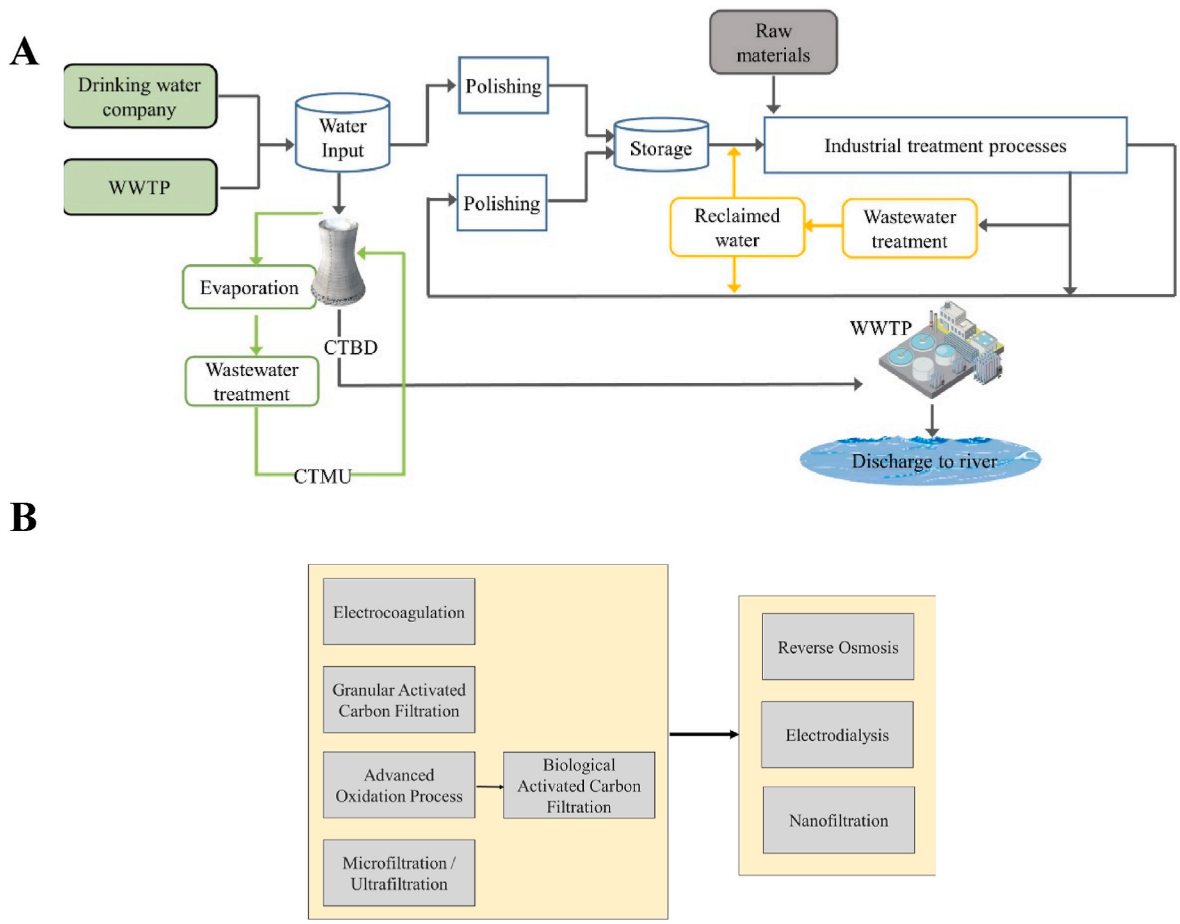

Fig. 3. Current process flow diagram (A) and water treatment options for CTBD (B) in chemical industry 1.

Real-time monitoring services for the related parameters, including corrosion, pH, temperature, hardness, TOC, conductivity and dissolved ions concentration in several locations are needed to feed and be connected with the digital services. In-process and in-factory modelling are applicable by developing mathematical process models and formulating mass balances within the system, respectively. To this end, water supply, demand and losses are quantified, the removal efficiency of pollutants, required energy and chemicals are predicted and the overall performance is assessed. Data availability and analysis facilitate the development of first principle, data-driven or hybrid models to predict the processes' performance and determine the most technical- and cost-efficient solution. However, environmental pollution is a key factor, making the LCA tool as an imperative environmental management tool to assess its impact (Hashemi et al., 2022). The developed components (water treatment processes, modelling, simulation, monitoring, data analytics, optimization and LCA) are integrated into the WaterCPS platform, creating the digital system and enabling operators to make decisions more easily and intelligently.

3.1.3. Assessment and expected output

As far as CTBD treatment is concerned, a promising trial is GAC-UF-RO to remove TOC, turbidity, suspended solids, conductivity, and dissolved ions. Shang et al. (2019) demonstrated that the adsorption-UF-RO treatment train resulted in the removal of 99.5% turbidity, 98.5% TDS, 98.0% conductivity, 87.4% dissolved organic carbon (DOC) and >97.8% ions, highlighting the necessity to pretreat the wastewater stream before the membrane filtration processes. Jang et al. (2017) found out that the activated carbon-UF-RO system achieved a reduction of 99.4%, 88.9% and 96.1% in COD, TN and conductivity, respectively. The WaterCPS platform aims to monitor and control the treatment train in order to provide advisory information and allow optimization. In this way, an increase in water savings and decrease in energy consumption are expected. Data analysis (descriptive and predictive analytics), modelling and simulation activities, optimization and LCA should be performed in this case study to predict, optimize and assess the expected outcome. The platform constitutes the basis for an advanced automated control system.

To assess the impact of the proposed actions, case-specific indicators are selected to build a baseline scenario for the process industry (Table 2). Water Sustainability refers to the amount of water savings, i.e., freshwater intake reduction. In this case, an approximately 15% decrease is expected. The Water-Eco Indicator refers to the amount of reused water (CTBD) within the factory. Contaminants removal is assessed through the indicator of "Improved water quality". In addition, dynamic LCA estimates indicators related to the environmental impact. Water footprint and carbon footprint are included. When nitrogen and phosphorus content exceed an acceptable level, it becomes harmful to aquatic organisms due to DO deficiency, causing eutrophication. In this regard, ecotoxicity and human toxicity are examined (Naushad, 2018). The infrastructure is digitally upgraded by deploying modelling, simulation, real-time monitoring devices, descriptive and predictive analytics, optimization and LCA tools across the value chain.

3.2. Chemical industry 2

3.2.1. Evaluation of the current situation and definition of targets

Freshwater for the chemical industry 2 derives from a nearby lake and river. The former appears to have fluctuations in TOC level and the latter in salinity. The process flow diagram of the current water management is shown in Fig. 4-A. Coagulation/flocculation process

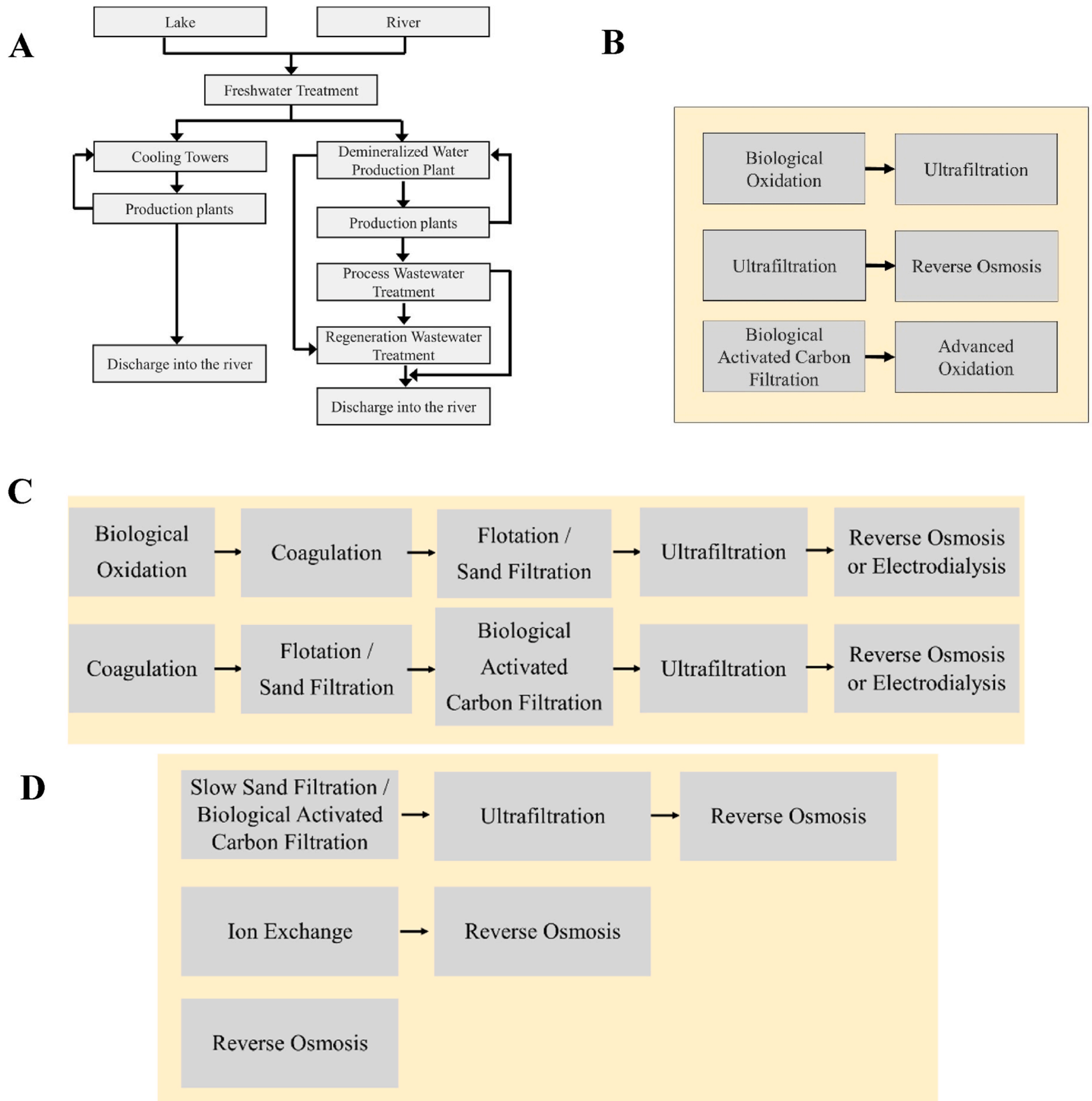

Fig. 4. Current process flow diagram (A), wastewater treatment options for the condensate (B), CTBD (C) and freshwater (D) in chemical industry 2.

combined with rapid sand filtration have been implemented to treat freshwater before supply it to the CTs. The demineralization (demin) plant consists of IEX using different resins. Both CTs and demin production plant result in CTBD and condensate generation, respectively, which are supplied to the production plants for steam generation and other utilities. Finally, the wastewater is discharged to a nearby river after having been treated in the WWTP.

In terms of information and communications technology (ICT) sources, data is collected in various locations by sensors. Water quality parameters, including temperature, pH, conductivity, TOC and DOC have been integrated. Digital and circular tools will allow constant control of the system. The fundamental objective is the reduction of the freshwater intake by incorporating fit-for-purpose processes and closing the water loops through recycling among the industrial process units. More specifically, the goal is to increase water savings by 1.1 million m^3/y.

3.2.2. *Investigation*

Target contaminants to be removed are selected concerning required quality for reuse as CTMU (see Table A2) or demineralized water, which must have low levels of minerals and conductivity. Firstly, freshwater used to produce demineralized water, after coagulation/flocculation and rapid sand filtration, has high TOC levels. Caltran et al. (2020) showed that IEX resins decrease the TOC by 40–60%. Ions of unacceptable concentration are adsorbed onto resins, which are alkaline or acidic. The former removes anions (Cl^-, HCO_3^-, etc.) and the latter cations (Ca^{2+}, Na^+, Mg^{2+}, etc.), resulting in ion separation from wastewater (Sengupta, 2018). Based on the target pollutants, alternative treatment trials are designed (Fig. 4-B). Pressure-driven membrane processes remove organics and ions. UF separates the organic matter and mitigates the membrane fouling, acting as a protective barrier to RO. RO can remove small particles, including monovalent ions and bacteria, up to 99.5% (Ezugbe and Rathilal, 2020). Salahi et al. (2011) demonstrated the high removal efficiency of the UF-RO system in relation to TSS (100%), TDS (95%), TOC (98%) and COD (98%). Deep bed filtration removes particles very effectively (Jegatheesan and Vigneswaran, 2005; Lim et al., 2022).

On the other hand, CTBD can be reused in CTs as make-up water, whose composition affects the CTs' performance. The better the quality of CTMU water, the higher the water recovery. To this end, CTBD is treated for the removal of contaminants and then reused as CTMU water. A main indicator is electrical conductivity, which favors the cooling system at low levels. This is due to minor corrosion and scaling since lower salt content and other relevant compounds characterize the feed water. The possible treatment options for CTBD and condensate are shown in Fig. 4-C and Fig. 4-D, respectively, focusing on the removal of organic matter and dissolved ions from the wastewater.

Internal recycling and near-ZLD comprise primary goals. The performance of each process is predicted by using first-principle or machine-learning models (in-process modelling) and enhanced by optimization services. Moreover, sensor installation across the network opens the way to a fully digital control system. Smart digital tools aspire to improve the plant's effectiveness through cognitive capabilities, which are core characteristics of Industry 5.0 (European Commission, Directorate-General for Research and Innovation, 2021). In this regard, the collaboration of data analytics, IoT, artificial intelligence, CPS, cognitive computing and human beings becomes feasible (Maddikunta et al., 2022). The simulated process models, data analytics, optimization, and dynamic LCA are incorporated into the WaterCPS.

3.2.3. Assessment and expected output

The performance of similar treatment systems as those recommended in this study were investigated to assess the removal efficiency for the various pollutants. It has been proven that the treatment of wastewater derived from a metal finishing industry by the UF-RO system removes 92.4% of conductivity, 95% of phosphorus and complete removal of SS, NH_4^+-N, chloride, sulfate, COD and BOD_5 (Petrinic et al., 2015). The BACF-UF-RO system was used in the study of Müller et al. (2024) to treat the CTBD, achieving the removal of 95.9%, 96.9%, 99.6%, 93.2%, 99.8%, 99.9%, 96.3% and 99.8% in conductivity, turbidity, TOC, sodium, calcium, magnesium, chloride and sulfate, respectively. Racar et al. (2017) found out that the treatment train of SF-UF-nanofiltration (NF)-NF-RO can result in the reduction of 90.9%, 96.0%, 92.7%, 98.5%, 94.3%, 84.9%, 85.5% and almost 100% in EC, turbidity, DOC, COD, TC, NO_3-N, NH_4-N and PO_4-P, respectively, of a secondary effluent. Racar et al. (2019) studied the performance of the coagulation-sand filtration-UF system for the wastewater treatment derived from a rendering plant, which proved to decrease the membrane fouling significantly and remove several pollutants from a secondary effluent. Specifically, turbidity, DOC, COD, nitrate, sulfate and sodium was decreased by up to 99.9%, 93.5%, 99.9%, 91.1%, 92.5% and 18.2%, respectively. Lin et al. (2013) investigated the performance of the oxidation (with $KMnO_4$)-UF system for pre-treated with sand filtration water samples and found out that the removal efficiency was up to 90.0% for turbidity, 27.3% for TOC, 60.0% for iron and 7.5% for calcium. Ioannou et al. (2013) carried out experiments for winery wastewater treatment by an RO unit, which removed 97.3% of COD, 67.0% of TN, 76.2% of TP, 93.9% of TSS and 94.5% of conductivity.

Improvement actions strive to fulfil the requirements for different water uses within the plant and achieve the goals as defined by the performance indicators (Table 2). Firstly, freshwater intake can be reduced through CTBD and condensate treatment and reuse. TOC and conductivity levels are set as indicators because of their importance to the system's operation (Saha et al., 2020). Better quality and higher recovery can be accomplished by conducting pilot- or industrial-scale experiments in the CTs. Online sensors measure and collect the required data, including pH, temperature, specific ion concentrations, hardness, and corrosion. Hence, scaling and fouling issues can be dealt with. As a last performance indicator, the chemical plant aspires to operate for 8 years consecutively without turnaround after the integration of all innovation tools.

The synergistic action of technological, circular and digital tools enhances water circularity significantly. Modelling and simulation tools enable the prediction of output flows, quality, energy requirements and chemical consumption. Descriptive and predictive analytics provide information based on the collected data. The former includes data analysis of the monitored quality parameters to define any deviation tendency over time and to determine the correlation among parameters. It enables the detection of unusual behavior of the monitored quality parameters and sets alerts to the system. On the other hand, predictive analytics permits the behavioral prediction of the parameters in the future. Optimization services depend on the performance indicators, i.e., minimization of the freshwater intake or maximization of reused water. Constraints are set, such as quality limits and expenses. They address the optimal mixing of raw water sources, considering the seasonal fluctuations and water availability. Finally, the LCA of the alternative scenarios incorporates impact categories, such as water footprint, carbon footprint, global warming potential, water resource depletion and thermal pollution (Muralikrishna and Manickam, 2017; Naushad, 2018). Different data sources are used for data analytics, facilitating the decision-making process by the operators in the plant. Thus, the WaterCPS platform integrate all tools and allow the continuous monitoring, control and prediction of the system's behavior, serving as a digital shadow with cognitive capacity.

3.3. Oil refinery plant

3.3.1. Evaluation of the current situation and definition of targets

The industrial water demand is covered by abstracting freshwater from a lake and reusing treated wastewater derived from the WWTP. There are multiple water needs within the oil refinery, including the use of cooling water, firefighting water, demineralized water and for steam production. However, wastewater streams generation is a major issue. On the one hand, stream 1 (7200 m^3/d) consists of storm drain, rainwater and backwash water derived from the existing water reuse units, i.e., multi-media filtration, activated carbon filtration, UF and RO. On the other hand, stream 2 (48–72 m^3/d) consists of ballast water and hot wash water that is generated in the kerosene treatment unit. Streams 1 and 2 are mixed and treated in such a way so as to be reused for industrial purposes. Table 1 presents the composition of both wastewater sources.

Currently, the wastewater is treated on-site within the ballast water treatment plant (BWTP), whose configuration is shown in Fig. 5-A. The oil content is removed by titled plate separator (Han et al., 2017), and COD, suspended solids, and conductivity by coagulation/flocculation process (Amuda and Amoo, 2007; Zheng et al., 2011). The addition of sodium carbonate regulates the pH (Qin et al., 2018). Within DAF, the suspended particles collide with the injected air bubbles, constituting the aggregates, within the contact zone and the formulated aggregates along with the air bubbles and unattached floc particles are directed to the separation zone, where they form a layer at the surface of the DAF (Rajapakse et al., 2022; Swart et al., 2022). As far as the biological unit, it consists of activated sludge basins.

Currently, no sensors have been installed across the BWTP. The infrastructure of the biological treatment system includes sensors to monitor the temperature, pH and DO. There are 2 management options for the effluent, at the moment, depending on its composition: (1) to be discharged to the sea or (2) to be sent to the biological unit, then to the final clarifier and finally discharged to the sea. Before the discharge point, chemical analysis is carried out in the laboratory. The target contaminants are COD, suspended solids, chlorides, oil, sulphur, ammonium nitrogen, phenol and iron.

3.3.2. Investigation

Wastewater derived from the petroleum industry requires suitable treatment, e.g., by a membrane biological reactor (MBR), before discharged to the receiving environment (Mansour et al., 2024). One of the main objectives of the oil refinery plant is to keep the wastewater quality within the acceptable range of discharge limits for 90% of the year. In addition, the increase of reused water by at least 50% compared to the

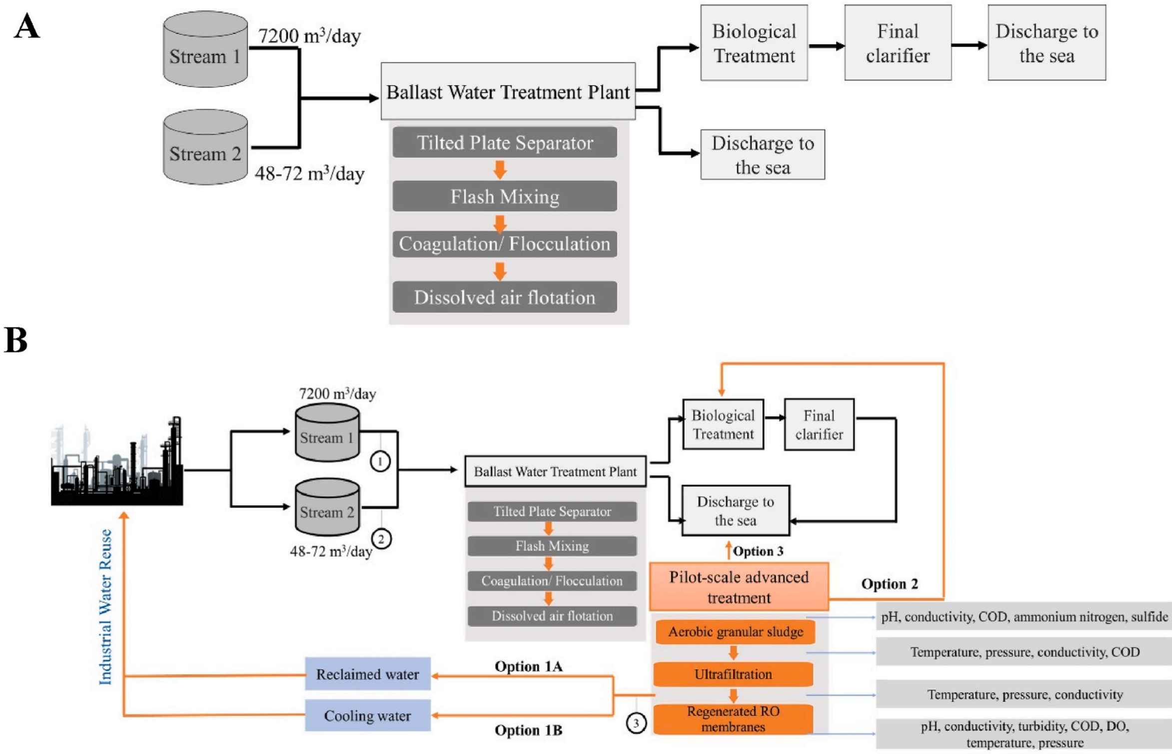

Fig. 5. Current process flow diagram (A) and alternative options of the to-be scenario (B) in the oil refinery plant.

amount of treated wastewater with the new technologies along with freshwater intake reduction are two important objectives. Water reuse entails less wastewater discharge. Laboratory chemical analysis is carried out to investigate the composition of the treated wastewater. The BWTP effluent's composition and quality criteria for biological treatment, industrial reuse and discharge limits into the sea are shown in Tables 1 and 3, respectively.

There is the potential for reuse and recycling through closed-water loops since reclaimed water could be used as drum wash water, stripped sour water, make-up water, coke-cutting water or for desalination. To achieve this goal, organic matter and nitrogen removal are feasible with AGS technology, operating in a sequencing batch reactor. The growth of dense, stable aerobic granules with excellent settling ability results in the successful separation of the liquid-solid phase (Ni and Yu, 2010; van Dijk et al., 2020). Therefore, salts, ions, and conductivity could be reduced by a membrane-based process, such as RO (Sahinkaya et al., 2019). It is also possible to directly treat only stream 2 due to its higher pollutant load, instead of the BWTP's effluent.

To ensure optimal performance of processes, it is deliberate to adopt a circular approach. First-principle models will predict the effluent's quality and facilitate the decision-making for alternative reuse practices. Monitoring tools must be included during the mixing process to control the quality and mixing ratio of sources. Real-time sensors and flowmeters (on-and-off devices) are to be installed across and at the outlet of the treatment train to monitor and allocate the water to the alternative options based on its composition. The BWTP's performance is strongly dependent on the water quality of the input stream. In this regard, the mixing process can be optimized in such a way so as to result in the desired water quality. All digital tools will be integrated into the WaterCPS platform to control the overall system.

Table 3
Limits for quality parameters of wastewater regarding four options.

Quality parameter	Unit	Biological unit	Firefighting water	Cooling tower	Discharge limits	BWTP Effluent
pH	–	9.00	7.50–8.50	7.50–8.50	6.00–9.00	12.20
Conductivity	μS/cm	<2500	1500	200.00–250.00	–	13100
Temperature	°C	–	–	–	30.00	–
Phenol	mg/L	–	–	–	1.00	1.40
COD	mg/L	700 (200–750)	–	–	200.00	10200
Sulphur	mg/L	10 (1–25)	–	–	1.00	–
Ammonium nitrogen	mg/L	20 (10–30)	–	–	20.00	6.96
TSS	mg/L	50.00	10.00	10.00	60.00	254
TDS	mg/L	–	–	–	–	8256
Oil	mg/L	100.00	3.00	0.50	10.00	–
Chloride	mg/L	–	300.00	0.00–50.00	1500	–
Iron	mg/L	–	–	0.00–0.30	<10	–
Sodium	mg/L	–	–	0.00–10.00	–	2330
Calcium	mg/L	–	–	0.00–80.00	–	–
Magnesium	mg/L	–	–	0.00–20.00	–	–
Total alkalinity	mg/L	–	–	0.00–80.00	–	–
Silica	mg/L	–	–	0.00–5.00	–	–

3.3.3. Assessment and expected output

Critical decisions are made at the outlet of the BWTP through an automatic valve. If the composition allows wastewater to be biologically treated, then it will be sent to the biological unit. Otherwise, it will enter the advanced treatment train. Fig. 5-B describes the process flow diagram of the system, from the inlet wastewater streams 1 and 2 to the alternative treatment options of BWTP's effluent.

Regarding the AGS, granules are ideal for biomass separation in the same reactor because of their settling capacity. Also, organic loading rate and high biomass concentration favor the production of water of high quality (Ni and Yu, 2010). Afterward, salts removal and conductivity reduction are achieved by RO. However, the excessive number of RO modules disposed of hampers the transition to a holistic sustainable process industry. For this reason, their reuse and recycling potential arises through the deployment of end-of-life membranes. The regeneration leads to higher membrane permeability and a sufficient removal rate (De Paula et al., 2017). To prevent their damage, UF membranes are installed as a pre-treatment step. Based on previous studies, the removal efficiency of AGS-UF-NF has been proven to be 90.2%, 90.1% and 91.8% for COD, TN and TP, respectively (L. Wang et al., 2018). Furthermore, around 99.0% of COD was removed from a wastewater stream treated by AGS and MBR (with UF membrane in submerged configuration) in-series (Di Trapani et al., 2019). In another study, the treatment train AGSMBR (with MF membrane)-RO achieved 99.9%, 99.7% and almost 100% removal of DOC, ammonium nitrogen and TP, respectively (S. Wang et al., 2020).

The proposed real-time sensors in the proposed pilot plant are shown in Fig. 5-B. Flow meters are recommended in feed streams and the mixing process. The sensors will be connected to the WaterCPS platform, facilitating the data analysis and optimization services. In addition, dynamic LCA examines the environmental impact of the improvement actions. In this case, water footprint, which is related to the reused water, and carbon footprint are considered important. In addition, eutrophication can be investigated by measuring COD, ammonium nitrate, and phenol. Eco-toxicity and human toxicity also contribute to the assessment of the system's upgrade. As is reflected in the performance indicators of this case, 1.3 million m^3 is aspired to be saved per year and 50% of the reclaimed water to be reused for industrial purposes. Digital tools and services are key components, including real-time monitoring, sensors, modelling, simulation, data analytics, optimization and LCA. The integration of all services into the WaterCPS platform makes feasible the environmental protection, releasing wastewater in the sea according to the established legislation by 90% of the year. Overall, the treatment methods of petrochemical industrial wastewater offer the opportunity to incentive and guide other similar process industries.

3.4. Meat production industry

3.4.1. Evaluation of the current situation and definition of targets

Freshwater sources comprise a river and a water company, which supply the factory with 700 m^3/d and 400 m^3/d, respectively. It is provided to the slaughterhouse production site (900 m^3/d), thermal power plant (100 m^3/d), and cooling units (100 m^3/d). Water is also used for disinfection and washing purposes of the operational equipment. The meat production plant processes approximately 150,000 kg of meat products on a daily basis, resulting in the production of 900–1000 m^3 of wastewater/d that contains a variety of pollutants. The high organic content is a matter of environmental concern to be addressed (Chen et al., 2021). During warm periods, the wastewater quantity increases due to higher demand for meat products and cooling processes. Currently, the wastewater is treated in the WWTP, which consists of conventional technologies (rotating screen filter, coagulation/-flocculation and DAF) before discharging into the city sewer network. The effluent's composition is shown in Table 1 and the current process flow diagram in Fig. 6.

Regarding closed-water loops, the water used for washing the transportation system (boxes, vehicles) is disinfected to be reused within the same process. In addition, the transport of feathers requires the consumption of water, which is reused for the same procedure. As far as monitoring and process optimization, it is essential to incorporate sensors, which will interconnect with the WaterCPS platform. Currently, neither sensors nor platforms are available. The only manual meters implemented are located in both the inlet point of raw wastewater and the inlet of WWTP. Finally, the industry has at its disposal software to provide information about raw materials, poultry processing, meat products offered for sale and their distribution.

3.4.2. Investigation

Considering the increased demand for meat products by 40% in the last decade and the high water demand for their production (Ragasri and Sabumon, 2023), it is important to investigate and incorporate solutions for enhanced water efficiency and circularity in slaughterhouses. Wastewater quality and the intention for water reuse determine the process innovations. Typical parameters for slaughterhouse effluents include COD, BOD, TOC, TP, NH_3, TN and TSS (Sandoval et al., 2024; Yetilmezsoy et al., 2022). Based on the wastewater characterization, the concerning contaminants are BOD, COD, TSS, nitrogen, and phosphorus. To this end, a biological, a separation and a disinfection process are

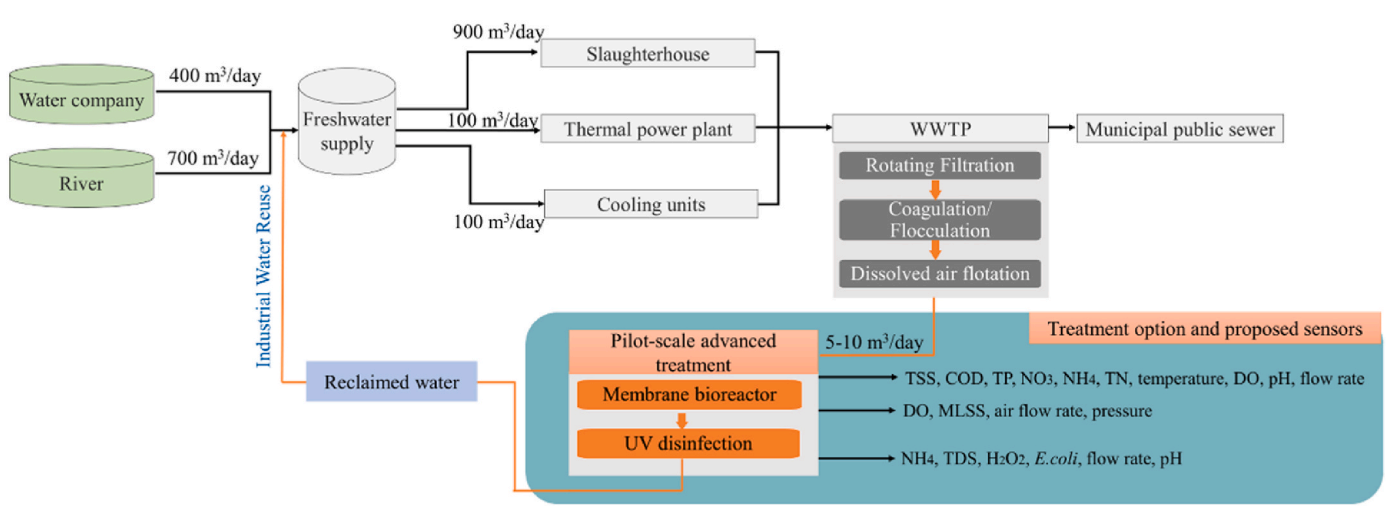

Fig. 6. Process flow diagram of the water/wastewater line in the meat production plant and interventions related to process, circular and digital tools (blue box) in the meat production plant. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

necessary. Accordingly, an MBR activated sludge system, comprising an anoxic and aerobic zone coupled with a UF membrane system, was selected. The MBR system aims at removing organic compounds, nitrogen, phosphorus, suspended and fine solids (Petta et al., 2017). Moreover, in order to comply with the food industry water quality requirements related to the absence microbial organisms, an ultra-violet system was employed to inactivate and kill any harmful pathogenic organisms.

Treated wastewater is an alternative water source. Environmental impact will decrease, considering that waste production and disposal are prevented and raw material supply decreases. In addition, the plant benefits economically due to the lower quantity of supplied water and tax payments in terms of environmental pollution. Each process unit is monitored dynamically and modelled, predicting the effluent's quality. In addition, an extended model across the value chain of the plant reinforces efficient water use, reuse, and management. Input and output data regarding flow rates, composition, capacity of treatment processes, and sensors are the tools for developing a model to predict the in-factory operations. The slaughterhouse generates more wastewater than can be treated. For this reason, an alternative option is to send it to an industry of a different sector. Such a synergy optimizes water management, the prevention of excess wastewater discharge into the environment, and profits. Thus, industrial modelling is feasible when cooperation between industries from different sectors, by exchanging water and other relevant materials, occurs.

In addition, digital innovations support the new practices. Reflecting the physical system to a digital one facilitates the data distribution system, process dynamic monitoring through real-time online sensors connected to the WaterCPS platform, and control. Otherwise, offline sensors are an option. Based on historical data, the creation of soft sensors is possible for incorporating descriptive analysis of the monitored parameters. This way, data patterns and trends in changes or anomalies are detected. Furthermore, prescriptive analytics trigger warning signals in case of an emergency or data anomaly. Hence, long-term smart digital solutions are promoted.

3.4.3. Assessment and expected output

A daily production between 900 and 1000 m^3 industrial wastewater makes imperative the incorporation of water-efficient treatment technologies, combined with circular and digital tools. In-process modelling applies through mathematical models for removal rate, recovery, chemical consumption and energy requirement prediction. In case of anomalies or unexplained incidents (e.g., immense sludge production, low effluent flow rate), correction actions must be implemented. By providing all data to the WaterCPS platform, it is feasible to dynamically monitor the processes and calculate selective process-specific indicators. Water consumption and emissions can be assessed through the LCA indicators of water footprint and carbon footprint, respectively (Amutha, 2017). Eutrophication and eco-toxicity, as well as human toxicity due to the presence of heavy metals, are considered (Mu et al., 2019). The next step of the CWEF includes the deployment of technologies, closed-loop practices, and digital tools, as indicated in the blue box of Fig. 6. The treated water can be reused as feed water to the slaughterhouse. Optimization is required if water is distributed for multiple goals, e.g., as freshwater source of the slaughterhouse or for cooling purposes.

Lastre-Acosta et al. (2020) proved that the wastewater treatment by MBR and ozonation in-series can result in the reduction of 96.5%, 94.4% and 96.8% in TOC, BOD_5 and COD, respectively. Based on the results of another study, the treatment train of MBR-UV reached a 95.7%, 99.5%, 72.7%, 90.0% and almost 100% reduction in COD, BOD_5, TP, NH_4^+-N and total coliform, respectively (Najafi et al., 2023). In addition, the study of Ongena et al. (2023) proved that the removal efficiency of the MBR-UV system was around 97.3% for turbidity, 94.5% for COD and 94.0% for NH_4^+-N.

WaterCPS will be connected with the online sensors, provided with data (both from online and offline measurements) to facilitate water use and reuse. To assess the impact of the implemented actions, relevant indicators are selected, as summarized in Table 2.

4. Conclusions

In this study, the already developed framework related to water-efficient process industries (CWEF) was applied to four extensive water-intensive case studies, aspiring to materialize the three innovation pillars (process, circular and digital) and strengthen their capacity towards sustainable water and wastewater use, management, recovery, reuse and recycling.

After setting a baseline assessment, potential improvement actions for all pillars were examined and assessed, taking into account a set of proposed performance indicators that were determined based on the industry-oriented requirements and peculiarities. The multi-level innovation pillars aim at enhancing the system's efficiency and water circularity, e.g., freshwater intake reduction, water reuse increase, closed-loop practices, wastewater discharge decrease, synergistic network creation, along with improved smart and cognitive ICT technologies, e.g., modelling and simulation activities, data analytics, optimization, LCA, real-time monitoring and a WaterCPS platform. Thus, the key conclusions of this study are as follows:

- Flexibility and fit-for-purpose approaches to the industrial sector are decision factors for a process industry that aspires to enhance water circularity.
- A composite of technological solutions (process pillar), closed-water loops (circular pillar) and digital services (digital pillar) represents an impactful, beneficial solution.
- Innovative technologies have to be incorporated for water/wastewater treatment, e.g., MBR and AGS, combining them with conventional ones.
- The implementation of closed-water loops should pursue the fit-for-purpose reuse and recycling water quality requirements.
- Digital services encompass process modelling and simulation, data analytics (descriptive and predictive), monitoring through online, offline and soft sensors, real-time monitoring platforms connected to the diverse data sources, optimization and dynamic LCA, which are integrated into a holistic water cyber-physical system platform to facilitate the decision-making process by the operators. This system is a digital representation of the physical system, i.e., a digital twin.

Industrial partners and stakeholders can exploit the outcomes of this study as a tool to select the most suitable innovation pillars tailored to their necessities and lead the way towards a sustainable industrial sector. The application of the framework will facilitate the replicability to other industries and act as a recommendation tool. Accordingly, further research should focus on creating guidelines on wastewater treatment for intra-factory closed-water loop practices and strategies to bridge the gap among different actors that exchange by-products.

CRediT authorship contribution statement

Efthalia Karkou: Writing – original draft, Methodology, Investigation, Data curation. **Chuan Jiet Teo:** Writing – review & editing, Methodology, Conceptualization. **Nikolaos Savvakis:** Writing – review & editing, Investigation. **Johann Poinapen:** Writing – review & editing, Methodology, Conceptualization. **George Arampatzis:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

George Arampatzis reports financial support, article publishing charges, and travel were provided by H2020-AquaSPICE project

(European Commission, CE-SPIRE-07-2020, Horizon, 2020). Efthalia Karkou reports a relationship with Technical University of Crete that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

The research methodology and results presented are part of the H2020-AquaSPICE project (EC, CE-SPIRE-07-2020, Horizon 2020). This project has received funding from the European Union's Horizon-2020 research and innovation program under grant agreement No. 958396. The responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Union. The European Commission is not responsible for any use that may be made of the information contained therein. The authors would like to express their gratitude to all partners of the AquaSPICE project, who gave the team of the Technical University of Crete the opportunity to develop the above methodological analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122596.

Appendix Aa. Supplementary data

Table A1
Process and circular requirements of the process industries for wastewater management

Process industry	Wastewater stream	Scale	Purpose	Technology	Measured quality parameters	Influencing conditions	Digital services	Main results	Refe-rence
Chemical industry (Dow Benelux BV, Terneuzen, The Netherlands)	CTBD	N.D.	CTBD reuse in the CT itself	Electrochemical oxidation (ECO) with a boron-doped diamond and a Ti/RuO_2 mixed-metal oxide anode	Organic compounds, initial pH	pH, current density, flow rate, supporting electrolyte	Elementary data analysis	85% COD removal, 51% TOC removal, ECO is a candidate pre-treatment technology for CTBD	Saha et al. (2020)
Leather industry	Float wastewater after tanning	Pilot and Industrial	Minimization of the environmental impact of the used industrial water	Pilot-scale drums with steam heating system	Chromium (II) oxide concentration, pH, oil and grease content	pH, density, acid-base indicators for hide, shrinkage temperature	Elementary data analysis	Leather of appropriate composition is obtained to be directly reused without damaging the quality of the final product	de Aquim et al. (2019)
Oil distribution and refinery industry	Oily wastewater	Lab	Reuse as cooling tower make-up (CTMU) water	UF, RO	Total suspended solids (TSS), TDS, oil and grease, COD, TOC, turbidity	Temperature, transmembrane pressure (TMP), crossflow velocity, pH	Elementary data analysis	UF acts as a protective barrier to RO, UF-RO treatment train allows the direct reuse in the CT, 98% COD, removal, 95% TDS removal, 98% TOC removal. Complete elimination of oil and grease, TSS, and turbidity.	Salahi et al. (2011)
Food industry	Almond industry wastewater	Pre-industrial	Conductivity reduction, minimization of the discharged quantity	Electrodialysis (EDR)	Conductivity, pH, TOC, COD, SS, inorganic ions (Cl, NO_3^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+})	Voltage, electrolyte concentration, time	Elementary data analysis	Sufficient conductivity reduction (up to 0.5 mS/cm). Higher voltage resulted in higher current intensity and lower operation time.	Valero et al. (2015)
Slaughterhouse plant	Slaughterhouse wastewater	N.D.	Slaughterhouse wastewater treatment and process	Submerged membrane bioreactor (MBR) - UF membrane	COD, TOC, TN, TP, SS, pH, turbidity,	pH, Mixed Liquor Suspended Solids (MLSS),	Elementary data analysis	Effective MBR system in terms of removal: TOC (96%), COD	Gürel and Büyükgüngör (2011)

(continued on next page)

Table A1 (*continued*)

Process industry	Wastewater stream	Scale	Purpose	Technology	Measured quality parameters	Influencing conditions	Digital services	Main results	Refe-rence
			efficiency assessment		ammonium, nitrate nitrogen	initial concentration of TOC, COD, ammonium and nitrate		(97%), TN (44%), TP (65%), NH_4-N (99%)	
Kermanshah Oil Refining Company	Oil refinery wastewater	Pilot	Wastewater treatment for reuse as CTMU water	UF, Mixed bed ion exchange, Disinfection	pH, COD, TDS, turbidity, SiO_2, oil and grease, heterotrophic microorganisms	TMP, time	Elementary data analysis	57% COD, 80% TDS, 94% Turbidity, 67% SiO_2, 88% oil and grease, 99% heterotrophic microorganisms.	Hashemi et al. (2020)
Inland brackish water desalination plant (Kay Bailey Hutchison Desalination Plant, El Paso)	Brackish water	Lab	Treatment and reuse of municipal wastewater. Improve recovery in the RO and reduce the RO concentrate volume.	Ion exchange (IEX) (mixture of two strong-base anion (SBA) resins) followed by RO	TDS, pH, conductivity, SO_4^{2-}, Cl^-, Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, $CaSO_4$ concentration	Temperature, empty bed contact time (EBCT), flow rate, flux, cycle.	Sensors Process modelling	Prevention of $CaSO_4$ precipitation on the membrane. RO concentrate volume decreased by 50%. Sulfate scaling was eliminated. Chemicals can be avoided. RO concentrate used successfully as regenerant for the IEX resins.	Smith and Sengupta (2015)
Abattoir industry	Wastewater from different processes after screening and dissolved air flotation (DAF) unit	N.D.	Evaluation of the MBR during wastewater treatment	Submerged MBR	TSS, volatile suspended solids (VSS), COD, Biochemical oxygen demand (BOD_5), pH, conductivity, ammonia, orthophosphate, nitrogen, microorganisms (fecal coliforms, *Listeria*, *Salmonella*)	DO, flux, TMP, time	Data analysis	MBR is a potential technology for treat wastewater to be reused for agricultural purposes	Keskes et al. (2012)
Poultry industry	Bird washer and Chiller wastewater	Lab	Evaluation of different UF membranes performance and Wastewater treatment for reuse and recycling purposes	UF	BOD, COD, TSS, oil and grease, TDS, proteins, Total Kjeldahl Nitrogen (TKN), pH	Feed flow rate, inlet pressure, permeate flux, membrane characteristics	Elementary data analysis	Efficient removal of TSS, fat, oil and grease (FOG). Removal rate of COD, BOD, TDS, TKN and protein content increased with decreasing nominal molecular weight cut-off.	Malmali et al. (2018)
Chemical company (Dow, Terneuzen, The Netherlands)	CTBD	Lab	Economical evaluation of CTBD treatment of high DOC for reuse	Coagulation, powdered activated carbon (PAC) adsorption, UF, RO	Temperature, TSS, conductivity, pH, BOD, turbidity, DOC, PO_4^{3-}, total Fe, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, silica, NO_3^-, Mn^{2+}, F^-, Ba^{2+}, Sr^{2+}	Coagulation: pH, coagulant dosage PAC adsorption: PAC concentration, contact time. UF: time, transmembrane pressure. RO: Flux, time.	Elementary data analysis	The optimal treatment train was PAC-UF-RO, which reduced DOC, turbidity, and TSS.	Löwenberg et al. (2015)
Wastewater Treatment Plant (WWTP) of Puente de los Vados, Granada, Spain	Municipal wastewater	Pilot	Quantification of removal efficiency and kinetic parameters	MBR	Temperature, conductivity, pH, DO, COD, BOD_5, TSS, VSS, TP, NH_4^+, NO_2^-, NO_3^-	Flow rate, hydraulic retention time (HRT), recycling rate, time	Sensors Elementary data analysis	65.17% ± 7.41% nitrogen removal, 91.97% ± 2.96% COD removal, 99.07% ± 0.57% BOD_5 removal	Leyva-Díaz et al. (2013)
Meat-processing plants in Ontario, Canada	Slaughterhouse wastewater	Lab	Evaluation of the AOP as post-treatment method and investigation of	AOP (UV/H_2O_2)	TOC, BOD, TN, COD, TP, TSS, pH	Flow rate, recycle ratio, lamp output power, wavelength,	Data analysis Process modelling Optimization	81% TOC removal and residual H_2O_2 was less than 2% (TOC_{in} = 24 mg/	Bustillo-Lecompte et al. (2016)

(*continued on next page*)

Table A1 (*continued*)

Process industry	Wastewater stream	Scale	Purpose	Technology	Measured quality parameters	Influencing conditions	Digital services	Main results	Refe-rence
			multiple parameters			hydrogen peroxide solution		L, H_2O_{2in} = 860 mg/L, Q_{in} = 15 mL/min, recycle ratio = 0.18). H_2O_{2in} and Q_{in} affected the TOC removal and the residual H_2O_{2in} the most.	
Textile factory	Effluent after secondary wastewater treatment	N.D.	Investigation of several parameters on ozonation efficiency	Ozonation	pH, COD, BOD_5, colour, NH_3-N, TP, TN, suspended solids	COD and colour at the inlet, ozonation time, ozone dose	Elementary data analysis	COD and colour decreased up to 95.2% and 95.4%, respectively.	Yin et al. (2017)
Textile district of Como	Mixed municipal-industrial wastewater	Lab	Evaluation of the system's efficiency	Activated granular sludge (AGS)	COD, BOD_5, TSS, VSS, TKN, NH_4-N, TN, TP, pH, colour	HRT, organic loading rate (OLR), time	Sensors Elementary data analysis	The technology is appropriate to be used for wastewater treatment because of high removal rate of COD, TSS and TKN.	Lotito et al. (2014)
Coking wastewater treatment plant (CWTP)	Coking wastewater discharged from a steel mill	Industrial	Mathematical simulation and operation optimization of CWTP	Aeration-anoxic-aeration biological process	COD, pH, NH_4-N, TKN, TSS	F/M ratio, DO, sludge return ratio, time	Online monitoring Data analysis Process modelling and simulation Optimization	Successful prediction of the COD and NH_4-N removal efficiency. Optimization of the CWTP's operation and cost estimation (€/m^3 wastewater)	Wu et al. (2016)
Slaughterhouse	Slaughterhouse wastewater	–	Life cycle impact assessment (LCIA) of different wastewater treatment methods	Coagulation & Flocculation, DAF, MBR, AOP	Alkalinity, pH, COD, BOD, TOC, TSS, FGO, TN, TP, SO42-, Nickel, Lead, Copper, Cadmium	Power, time, feed composition, flow rate, chemicals	Elementary data analysis Process modelling and simulation LCA	The optimal scenario for industrial water reuse included also tertiary treatment, reducing the overall footprint up to 2.195 milliEcopoints.	Teo et al. (2023)

N.D. = Not Defined.

Table A2
Water quality criteria for cooling towers (Source: EPRI, 2008)

Quality parameter	Unit	Cooling water for cooling tower
Ca x SO_4	mg/L x mg/L	500000
Mg x SiO_2	mg/L $CaCO_3$ x mg/L SiO_2	35000
Silica	mg/L	150.00
Iron	mg/L	<0.50
Manganese	mg/L	<0.50
Copper	mg/L	<0.10
Aluminium	mg/L	<1.00
Sulphur	mg/L	5.00
Ammonia	mg/L	<2.00
Total dissolved solids	mg/L	<70000
Total suspended solids	mg/L	<100 (standard film fill)/<300 (open or splash film fill)

References

Abdel-Shafy, H.I., Shoeib, M.A., El-Khateeb, M.A., Youssef, A.O., Hafez, O.M., 2020. Electrochemical treatment of industrial cooling tower blowdown water using magnesium-rod electrode. Water Resour. Ind. 23, 100121. https://doi.org/10.1016/j.wri.2019.100121.

Altman, S.J., Jensen, R.P., Cappelle, M.A., Sanchez, A.L., Everett, R.L., Anderson, H.L., McGrath, L.K., 2012. Membrane treatment of side-stream cooling tower water for reduction of water usage. Desalination 285, 177–183. https://doi.org/10.1016/j.desal.2011.09.052.

Amuda, O.S., Amoo, I.A., 2007. Coagulation/flocculation process and sludge conditioning in beverage industrial wastewater treatment. J. Hazard Mater. 141, 778–783. https://doi.org/10.1016/j.jhazmat.2006.07.044.

Amutha, K., 2017. Sustainable chemical management and zero discharges. In: Sustainable Fibres and Textiles. Elsevier Ltd, pp. 347–366. https://doi.org/10.1016/B978-0-08-102041-8.00012-3.

Arora, M., Yeow, L.W., Cheah, L., Derrible, S., 2022. Assessing water circularity in cities: methodological framework with a case study. Resour. Conserv. Recycl. 178, 106042. https://doi.org/10.1016/j.resconrec.2021.106042.
Ashraf, A., Ramamurthy, R., Rene, E.R., 2021. Wastewater treatment and resource recovery technologies in the brewery industry: current trends and emerging practices. Sustain. Energy Technol. Assessments 47, 101432. https://doi.org/10.1016/j.seta.2021.101432.
Azzaro-Pantel, C., Madoumier, M., Gésan-Guiziou, G., 2022. Development of an ecodesign framework for food manufacturing including process flowsheeting and multiple-criteria decision-making: application to milk evaporation. Food Bioprod. Process. 131, 40–59. https://doi.org/10.1016/j.fbp.2021.10.003.
Becker, D., Jungfer, C., Track, T., 2019. Integrated industrial water management – challenges, solutions, and future priorities. Chem. Ing. Tech. 91 (10), 1367–1374. https://doi.org/10.1002/cite.201900086.
Bellamoli, F., Di Iorio, M., Vian, M., Melgani, F., 2023. Machine learning methods for anomaly classification in wastewater treatment plants. J. Environ. Manag. 344 (118594). https://doi.org/10.1016/j.jenvman.2023.118594.
Bressanelli, G., Saccani, N., Perona, M., Baccanelli, I., 2020. Towards circular economy in the household appliance industry : an overview of cases. Resources 9 (128). https://doi.org/10.3390/resources9110128.
Bustillo-Lecompte, C.F., Ghafoori, S., Mehrvar, M., 2016. Photochemical degradation of an actual slaughterhouse wastewater by continuous UV/H2O2 photoreactor with recycle. J. Environ. Chem. Eng. 4, 719–732. https://doi.org/10.1016/j.jece.2015.12.009.
Büyüközkan, G., Tüfekçi, G., 2021. A multi-stage fuzzy decision-making framework to evaluate the appropriate wastewater treatment system: a case study. Environ. Sci. Pollut. Control Ser. 28, 53507–53519. https://doi.org/10.1007/s11356-021-14116-w.
Caltran, I., Heijman, S.G.J., Shorney-Darby, H.L., Rietveld, L.C., 2020. Impact of removal of natural organic matter from surface water by ion exchange: a case study of pilots in Belgium, United Kingdom and The Netherlands. Separation and Purification Technology 247, 116974. https://doi.org/10.1016/j.seppur.2020.116974.
Chen, Z., Wang, D., Dao, G., Shi, Q., Yu, T., Guo, F., Wu, G., 2021. Environmental impact of the effluents discharging from full-scale wastewater treatment plants evaluated by a hybrid fuzzy approach. Sci. Total Environ. 790, 148212. https://doi.org/10.1016/j.scitotenv.2021.148212.
da Luz, N., Tobiason, J.E., Kumpel, E., 2022. Water quality monitoring with purpose: using a novel framework and leveraging long-term data. Sci. Total Environ. 818, 151729. https://doi.org/10.1016/j.scitotenv.2021.151729.
Davood Abadi Farahani, M.H., Borghei, S.M., Vatanpour, V., 2016. Recovery of cooling tower blowdown water for reuse: the investigation of different types of pretreatment prior nanofiltration and reverse osmosis. Journal of Water Process Engineering 10, 188–199. https://doi.org/10.1016/j.jwpe.2016.01.011.
de Aquim, P.M., Hansen, É., Gutterres, M., 2019. Water reuse: an alternative to minimize the environmental impact on the leather industry. J. Environ. Manag. 230, 456–463. https://doi.org/10.1016/j.jenvman.2018.09.077.
De Paula, E.C., Gomes, J.C.L., Amaral, M.C.S., 2017. Recycling of end-of-life reverse osmosis membranes by oxidative treatment: a technical evaluation. Water Sci. Technol. 76 (3), 605–622. https://doi.org/10.2166/wst.2017.238.
Deshpande, P.S., Sharma, S.C., Peddoju, S.K., 2019. Security and Data Storage Aspect in Cloud Computing. Springer. https://link.springer.com/content/pdf/10.1007/978-981-13-6089-3.pdf.
Di Trapani, D., Corsino, S.F., Torregrossa, M., Viviani, G., 2019. Treatment of high strength industrial wastewater with membrane bioreactors for water reuse: effect of pre-treatment with aerobic granular sludge on system performance and fouling tendency. Journal of Water Process Engineering 31, 100859. https://doi.org/10.1016/j.jwpe.2019.100859.
EPRI, 2008. Use of Alternate Water Sources for Power Plant Cooling, vol. 1014935.
European Commission, Directorate-General for Research and Innovation, 2021. Petridis, Industry 5.0 – towards a Sustainable, Human-Centric and Resilient European Industry. Publications Office of the European Union. https://data.europa.eu/doi/10.2777/308407.
Ezugbe, E.O., Rathilal, S., 2020. Membrane technologies in wastewater treatment: a review. Membranes 10 (89). https://doi.org/10.3390/membranes10050089.
Feng, W., Liu, Y., Gao, L., 2022. Stormwater treatment for reuse : current practice and future development – a review. J. Environ. Manag. 301, 113830. https://doi.org/10.1016/j.jenvman.2021.113830.
Foglia, A., González-Camejo, J., Radini, S., Sgroi, M., Li, K., Eusebi, A.L., Fatone, F., 2023. Transforming wastewater treatment plants into reclaimed water facilities in water-unbalanced regions. An overview of possibilities and recommendations focusing on the Italian case. J. Clean. Prod. 410, 137264. https://doi.org/10.1016/j.jclepro.2023.137264.
GilPavas, E., Dobrosz-Gómez, I., Gómez-García, M.Á., 2017. Coagulation-flocculation sequential with Fenton or Photo-Fenton processes as an alternative for the industrial textile wastewater treatment. J. Environ. Manag. 191, 189–197. https://doi.org/10.1016/j.jenvman.2017.01.015.
Girolamini, L., Brattich, E., Marino, F., Pascale, M.R., Mazzotta, M., Spiteri, S., Derelitto, C., Tositti, L., Cristino, S., 2023. Cooling towers influence in an urban environment: a predictive model to control and prevent Legionella risk and Legionellosis events. Build. Environ. 228, 109891. https://doi.org/10.1016/j.buildenv.2022.109891.
Glatt, M., Sinnwell, C., Yi, L., Donohoe, S., Ravani, B., Aurich, J.C., 2021. Modeling and implementation of a digital twin of material flows based on physics simulation. J. Manuf. Syst. 58, 231–245. https://doi.org/10.1016/j.jmsy.2020.04.015.
Goonetilleke, A., Liu, A., Managi, S., Wilson, C., Gardner, T., Bandala, E.R., Walker, L., Holden, J., Wibowo, M.A., Suripin, S., Joshi, H., Bonotto, D.M., Rajapaksa, D., 2017. Stormwater reuse, a viable option : fact or fiction. Econ. Anal. Pol. 56, 14–17. https://doi.org/10.1016/j.eap.2017.08.001.
Griebe, T., Flemming, H.C., 1998. Biocide-free antifouling strategy to protect RO membranes from biofouling. Desalination 118 (1–3), 153–156. https://doi.org/10.1016/S0011-9164(98)00113-1.
Gürel, L., Büyükgüngör, H., 2011. Treatment of slaughterhouse plant wastewater by using a membrane bioreactor. Water Sci. Technol. 64 (1), 214–219. https://doi.org/10.2166/wst.2011.677.
Guven, H., Ersahin, M.E., Ozgun, H., Ozturk, I., Koyuncu, I., 2023. Energy and material refineries of future: wastewater treatment plants. J. Environ. Manag. 329 (117130). https://doi.org/10.1016/j.jenvman.2022.117130.
Han, Y., He, L., Luo, X., Lü, Y., Shi, K., Chen, J., Huang, X., 2017. A review of the recent advances in design of corrugated plate packs applied for oil–water separation. J. Ind. Eng. Chem. 53, 37–50. https://doi.org/10.1016/j.jiec.2017.04.029.
Hankins, N.P., Singh, R., 2016. Emerging membrane technology for sustainable water treatment. In: Emerging Membrane Technology for Sustainable Water Treatment. John Fedor. https://doi.org/10.1016/C2012-0-07949-5.
Hashemi, F., Hashemi, H., Abbasi, A., Schreiber, M.E., 2022. Life cycle and economic assessments of petroleum refineries wastewater recycling using membrane, resin and on site disinfection (UF-IXMB-MOX) processes. Process Saf. Environ. Protect. 162, 419–425. https://doi.org/10.1016/j.psep.2022.04.027.
Hashemi, F., Hashemi, H., Shahbazi, M., Dehghani, M., Hoseini, M., Shafeie, A., 2020. Reclamation of real oil refinery effluent as makeup water in cooling towers using ultrafiltration, ion exchange and multioxidant disinfectant. Water Resour. Ind. 23, 100123. https://doi.org/10.1016/j.wri.2019.100123.
Helmecke, M., Fries, E., Schulte, C., 2020. Regulating water reuse for agricultural irrigation: risks related to organic micro-contaminants. Environ. Sci. Eur. 32 (4). https://doi.org/10.1186/s12302-019-0283-0.
Hussain, C.M., 2020. Concepts of advanced zero waste tools: present and emerging waste management practices. In: Concepts of Advanced Zero Waste Tools: Present and Emerging Waste Management Practices. https://doi.org/10.1016/B978-0-12-822183-9.09991-8.
Iervolino, M., Mancini, B., Cristino, S., 2017. Industrial cooling tower disinfection treatment to prevent Legionella spp. Int. J. Environ. Res. Publ. Health 14 (10), 1–14. https://doi.org/10.3390/ijerph14101125.
Ilyas, E. Bin, Fischer, M., Iggena, T., Tonjes, R., 2020. Virtual sensor creation to replace faulty sensors using automated machine learning techniques. Global Internet of Things Summit (GIoTS) 1–6. https://doi.org/10.1109/GIOTS49054.2020.9119681, 2020.
Ioannou, L.A., Michael, C., Vakondios, N., Drosou, K., Xekoukoulotakis, N.P., Diamadopoulos, E., Fatta-Kassinos, D., 2013. Winery wastewater purification by reverse osmosis and oxidation of the concentrate by solar photo-Fenton. Separation and Purification Technology 118, 659–669. https://doi.org/10.1016/j.seppur.2013.07.049.
Isaac, R., Viaro, V., Fonseca, C., Mânica, A., 2022. Identification of key factors for urban—industrial water reuse: a multi-criteria analysis case study. Water 14 (1314). https://doi.org/10.3390/w14081314.
Jain, R., Nigam, H., Mathur, M., Malik, A., Arora, U.K., 2021. Towards green thermal power plants with blowdown water reuse and simultaneous biogenic nanostructures recovery from waste. Resour. Conserv. Recycl. 168, 105283. https://doi.org/10.1016/j.resconrec.2020.105283.
Jang, A., Jung, J.-T., Kang, H., Kim, H.-S., Kim, J.-O., 2017. Reuse of effluent discharged from tannery wastewater treatment plants by powdered activated carbon and ultra fi ltration combined reverse osmosis system. Journal of Water Reuse and Desalination 7 (1), 97–102. https://doi.org/10.2166/wrd.2016.001.
Jegatheesan, V., Vigneswaran, S., 2005. Deep bed filtration: mathematical models and observations. Crit. Rev. Environ. Sci. Technol. 35 (6), 515–569. https://doi.org/10.1080/10643380500326432.
Juneidi, S.J., Sorour, M.T., Aly, S.A., 2022. Proposed systematic approach for assessing different wastewater treatment plants alternatives: case study of Aqaba city (South Jordan). Alex. Eng. J. 61 (12), 12567–12580. https://doi.org/10.1016/j.aej.2022.06.044.
Kamble, S.S., Gunasekaran, A., Gawankar, S.A., 2018. Sustainable Industry 4.0 framework: a systematic literature review identifying the current trends and future perspectives. Process Saf. Environ. Protect. 117, 408–425. https://doi.org/10.1016/j.psep.2018.05.009.
Karkou, E., Savvakis, N., Arampatzis, G., 2022. Critical insights to drive sustainable water management in process industries. 1st International Conference on Sustainable Chemical and Environmental Engineering, pp. 184–185.
Kesari, K.K., Soni, R., Jamal, Q.M.S., Tripathi, P., Lal, J.A., Jha, N.K., Siddiqui, M.H., Kumar, P., Tripathi, V., Ruokolainen, J., 2021. Wastewater treatment and reuse: a review of its applications and health implications. Water Air Soil Pollut. 232 (208). https://doi.org/10.1007/s11270-021-05154-8.
Keskes, S., Hmaied, F., Gannoun, H., Bouallagui, H., Jacques, J., 2012. Performance of a submerged membrane bioreactor for the aerobic treatment of abattoir wastewater. Bioresour. Technol. 103, 28–34. https://doi.org/10.1016/j.biortech.2011.09.063.
Kuipers, N., van Leerdam, R., van Medevoort, J., van Tongeren, W., Verhasselt, B., Verelst, L., Vermeersch, M., Corbisier, D., 2014. Techno-economic assessment of boiler feed water production by membrane distillation with reuse of thermal waste energy from cooling water. Desalination Water Treat. https://doi.org/10.1080/19443994.2014.946722.
Kurniawan, T.A., Othman, M.H.D., Liang, X., Goh, H.H., Gikas, P., Kusworo, T.D., Anouzla, A., Chew, K.W., 2023. Decarbonization in waste recycling industry using digitalization to promote net-zero emissions and its implications on sustainability. J. Environ. Manag. 338, 117765. https://doi.org/10.1016/j.jenvman.2023.117765.

Lastre-Acosta, A.M., Palharim, P.H., Barbosa, I.M., Mierzwa, J.C., Silva Costa Teixeira, A. C., 2020. Removal of sulfadiazine from simulated industrial wastewater by a membrane bioreactor and ozonation. J. Environ. Manag. 271, 111040. https://doi.org/10.1016/j.jenvman.2020.111040.
Leyva-Díaz, J.C., Calderón, K., Rodríguez, F.A., González-López, J., Hontoria, E., Poyatos, J.M., 2013. Comparative kinetic study between moving bed biofilm reactor-membrane bioreactor and membrane bioreactor systems and their influence on organic matter and nutrients removal. Biochem. Eng. J. 77, 28–40. https://doi.org/10.1016/j.bej.2013.04.023.
Liberman, B., Eshed, L., Greenberg, G., 2020. Pulse Flow RO - the new RO technology for waste and brackish water applications. Desalination 479, 114336. https://doi.org/10.1016/j.desal.2020.114336.
Lim, S., Shi, J.L., von Gunten, U., McCurry, D.L., 2022. Ozonation of organic compounds in water and wastewater: a critical review. Water Res. 213, 118053. https://doi.org/10.1016/j.watres.2022.118053.
Lin, T., Pan, S., Chen, W., Bin, S., 2013. Role of pre-oxidation, using potassium permanganate, for mitigating membrane fouling by natural organic matter in an ultrafiltration system. Chem. Eng. J. 223, 487–496. https://doi.org/10.1016/j.cej.2013.03.024.
Lizot, M., Goffi, A.S., Thesari, S.S., Trojan, F., Afonso, P.S.L.P., Ferreira, P.F.V., 2021. Multi-criteria methodology for selection of wastewater treatment systems with economic, social, technical and environmental aspects. Environ. Dev. Sustain. 23 (7), 9827–9851. https://doi.org/10.1007/s10668-020-00906-8.
Lotito, A.M., De Sanctis, M., Di Iaconi, C., Bergna, G., 2014. Textile wastewater treatment: aerobic granular sludge vs activated sludge systems. Water Res. 54, 337–346. https://doi.org/10.1016/j.watres.2014.01.055.
Löwenberg, J., Baum, J.A., Zimmermann, Y.S., Groot, C., van den Broek, W., Wintgens, T., 2015. Comparison of pre-treatment technologies towards improving reverse osmosis desalination of cooling tower blow down. Desalination 357, 140–149. https://doi.org/10.1016/j.desal.2014.11.018.
Ma, K., Liu, M., Zhang, J., 2020. A method for determining the optimum state of recirculating cooling water system and experimental investigation based on heat dissipation efficiency. Appl. Therm. Eng. 176 (2), 115398. https://doi.org/10.1016/j.applthermaleng.2020.115398.
Ma, R., Zhang, Z., Justin, Lin, B., 2023. Evaluating the synergistic effect of digitalization and industrialization on total factor carbon emission performance. J. Environ. Manag. 348, 119281. https://doi.org/10.1016/j.jenvman.2023.119281.
Maddikunta, P.K.R., Pham, Q.V., B, P., Deepa, N., Dev, K., Gadekallu, T.R., Ruby, R., Liyanage, M., 2022. Industry 5.0: a survey on enabling technologies and potential applications. Journal of Industrial Information Integration 26, 100257. https://doi.org/10.1016/j.jii.2021.100257.
Malmali, M., Askegaard, J., Sardari, K., Eswaranandam, S., 2018. Evaluation of ultra fi ltration membranes for treating poultry processing wastewater. Journal of Water Process Engineering 22, 218–226. https://doi.org/10.1016/j.jwpe.2018.02.010.
Mansour, M.S.M., Abdel-shafy, H.I., Ibrahim, A.M., 2024. Petroleum wastewater: environmental protection, treatment, and safe reuse: an overview. J. Environ. Manag. 351, 119827. https://doi.org/10.1016/j.jenvman.2023.119827.
Matheri, A.N., Mohamed, B., Ntuli, F., Nabadda, E., Ngila, J.C., 2022. Sustainable circularity and intelligent data-driven operations and control of the wastewater treatment plant. Phys. Chem. Earth 126 (103152). https://doi.org/10.1016/j.pce.2022.103152.
Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S.J., Ulgiati, S., 2018. Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies. Environments 5 (24). https://doi.org/10.3390/environments5020024.
Melián-Martel, N., Sadhwani Alonso, J.J., Pérez Báez, S.O., 2013. Reuse and management of brine in sustainable SWRO desalination plants. Desalination Water Treat. 51 (1–3), 560–566. https://doi.org/10.1080/19443994.2012.713567.
Mhatre, P., Panchal, R., Singh, A., Bibyan, S., 2021. A systematic literature review on the circular economy initiatives in the European Union. Sustain. Prod. Consum. 26, 187–202. https://doi.org/10.1016/j.spc.2020.09.008.
Misrol, M.A., Wan Alwi, S.R., Lim, J.S., Manan, Z.A., 2021. An optimal resource recovery of biogas, water regeneration, and reuse network integrating domestic and industrial sources. J. Clean. Prod. 286, 125372. https://doi.org/10.1016/j.jclepro.2020.125372.
Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153. https://doi.org/10.1016/j.resconrec.2019.104553.
Mu, D., Xin, C., Zhou, W., 2019. Life cycle assessment and techno-economic analysis of algal biofuel production. In: Microalgae Cultivation for Biofuels Production. Elsevier Inc, pp. 281–292. https://doi.org/10.1016/B978-0-12-817536-1.00018-7.
Müller, S.I., Chapanova, G., Diekow, T., Kaiser, C., Hamelink, L., Hitsov, I.P., Wyseure, L., Moed, D.H., Palmowski, L., Wintgens, T., 2024. Comparison of cooling tower blowdown and enhanced make up water treatment to minimize cooling water footprint. J. Environ. Manag. 367 (121949). https://doi.org/10.1016/j.jenvman.2024.121949.
Muralikrishna, I.V., Manickam, V., 2017. Life cycle assessment. Environ. Manag. 1 (2), 57–75. https://doi.org/10.1016/B978-0-12-811989-1.00005-1. Elsevier Inc.
Najafi, M.S.S., Navid, C.S., Shayegan, A.B.J., 2023. Application of membrane bioreactor integrated with ultraviolet disinfection for simultaneous greywater treatment and SARS - CoV - 2 removal. Int. J. Environ. Sci. Technol. 20 (10), 11041–11048. https://doi.org/10.1007/s13762-023-05119-w.
Naushad, M., 2018. Life Cycle Assessment of Wastewater Treatment.
Nemati-Amirkolaii, K., Romdhana, H., Lameloise, M.L., 2021. A novel user-friendly tool for minimizing water use in processing industry. Cleaner Engineering and Technology 4, 100260. https://doi.org/10.1016/j.clet.2021.100260.
Ni, B.J., Yu, H.Q., 2010. Mathematical modeling of aerobic granular sludge: a review. Biotechnol. Adv. 28 (6), 895–909. https://doi.org/10.1016/j.biotechadv.2010.08.004.
Okorie, O., Salonitis, K., Charnley, F., Moreno, M., Turner, C., Tiwari, A., 2018. Digitisation and the circular economy: a review of current research and future trends. Energies 11, 3009. https://doi.org/10.3390/en11113009.
Ongena, S., Walle, A. Van De, Mosquera-romero, S., Driesen, N., 2023. Comparison of MBR and MBBR followed by UV or electrochemical disinfection for decentralized greywater treatment. Water Res. 235, 119818. https://doi.org/10.1016/j.watres.2023.119818.
Petrinic, I., Korenak, J., Povodnik, D., Hélix-Nielsen, C., 2015. A feasibility study of ultrafiltration/reverse osmosis (UF/RO)-based wastewater treatment and reuse in the metal finishing industry. J. Clean. Prod. 101, 292–300. https://doi.org/10.1016/j.jclepro.2015.04.022.
Petta, L., De Gisi, S., Casella, P., Farina, R., Notarnicola, M., 2017. Evaluation of the treatability of a winery distillery (vinasse) wastewater by UASB, anoxic-aerobic UF-MBR and chemical precipitation/adsorption. J. Environ. Manag. 201, 177–189. https://doi.org/10.1016/j.jenvman.2017.06.042.
Pham, T.T., Mai, T.D., Pham, T.D., Hoang, M.T., Nguyen, M.K., Pham, T.T., 2016. Industrial water mass balance as a tool for water management in industrial parks. Water Resour. Ind. 13, 14–21. https://doi.org/10.1016/j.wri.2016.04.001.
Preisner, M., Smol, M., Horttanainen, M., Deviatkin, I., Havukainen, J., Klavins, M., Ozola-Davidane, R., Kruopienė, J., Szatkowska, B., Appels, L., Houtmeyers, S., Roosalu, K., 2022. Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector. J. Environ. Manag. 304, 114261. https://doi.org/10.1016/j.jenvman.2021.114261.
Qin, J., Wang, H., Qin, C., Meng, H., Qu, W., Qian, H., 2018. The role of sodium carbonate in PAM coagulation-flocculation for oil acidized wastewater treatment. Water Sci. Technol. 77 (11), 2677–2686. https://doi.org/10.2166/wst.2018.224.
Quaglia, A., Pennati, A., Bogataj, M., Kravanja, Z., Sin, G., Gani, R., 2014. Industrial process water treatment and reuse: a framework for synthesis and design. Ind. Eng. Chem. Res. 53, 5160–5171. https://doi.org/10.1021/ie401379j.
Racar, M., Dolar, D., Farkaš, M., Milčić, N., Špehar, A., Košutić, K., 2019. Rendering plant wastewater reclamation by coagulation, sand filtration, and ultrafiltration. Chemosphere 227, 207–215. https://doi.org/10.1016/j.chemosphere.2019.04.045.
Racar, M., Dolar, D., Špehar, A., Košutić, K., 2017. Application of UF/NF/RO membranes for treatment and reuse of rendering plant wastewater. Process Saf. Environ. Protect. 105, 386–392. https://doi.org/10.1016/j.psep.2016.11.015.
Radini, S., Marinelli, E., Akyol, Ç., Eusebi, A.L., Vasilaki, V., Mancini, A., Frontoni, E., Bischetti, G.B., Gandolfi, C., Katsou, E., Fatone, F., 2021. Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: cyber-physical framework and innovations. Appl. Energy 298, 117268. https://doi.org/10.1016/j.apenergy.2021.117268.
Ragasri, S., Sabumon, P.C., 2023. A critical review on slaughterhouse waste management and framing sustainable practices in managing slaughterhouse waste in India. J. Environ. Manag. 327, 116823. https://doi.org/10.1016/j.jenvman.2022.116823.
Rahmani, K., 2017. Reducing water consumption by increasing the cycles of concentration and Considerations of corrosion and scaling in a cooling system. Appl. Therm. Eng. 114, 849–856. https://doi.org/10.1016/j.applthermaleng.2016.12.075.
Raimondi, A., Quinn, R., Abhijith, G.R., Becciu, G., Ostfeld, A., 2023. Rainwater harvesting and treatment : state of the art and perspectives. Water 15 (1518). https://doi.org/10.3390/w15081518.
Rajapakse, N., Zargar, M., Sen, T., Khiadani, M., 2022. Effects of influent physicochemical characteristics on air dissolution, bubble size and rise velocity in dissolved air flotation: a review. Separation and Purification Technology 289, 120772. https://doi.org/10.1016/j.seppur.2022.120772.
Ribeiro dos Santos, P., de Souza Leite, L., Daniel, L.A., 2022. Performance of biological activated carbon (BAC) filtration for the treatment of secondary effluent: a pilot-scale study. J. Environ. Manag. 302. https://doi.org/10.1016/j.jenvman.2021.114026.
Ricky, R., Shanthakumar, S., Ganapathy, G.P., Chiampo, F., 2022. Zero liquid discharge system for the tannery industry—an overview of sustainable approaches. Recycling 7 (31). https://doi.org/10.3390/recycling7030031.
Ruiz, J., Navarro, P., Hernández, M., Lucas, M., Kaiser, A.S., 2022. Thermal performance and emissions analysis of a new cooling tower prototype. Appl. Therm. Eng. 206, 118065. https://doi.org/10.1016/j.applthermaleng.2022.118065.
Saha, P., Bruning, H., Wagner, T.V., Rijnaarts, H.H.M., 2020. Removal of organic compounds from cooling tower blowdown by electrochemical oxidation: role of electrodes and operational parameters. Chemosphere 259, 127491. https://doi.org/10.1016/j.chemosphere.2020.127491.
Sahinkaya, E., Tuncman, S., Koc, I., Guner, A.R., Ciftci, S., Aygun, A., Sengul, S., 2019. Performance of a pilot-scale reverse osmosis process for water recovery from biologically-treated textile wastewater. J. Environ. Manag. 249, 109382. https://doi.org/10.1016/j.jenvman.2019.109382.
Sakamoto, H., de Sá Teles, B.A., Kulay, L., 2021. An eco-efficiency analysis of refinery effluent pretreatments for water reuse under a Zero Liquid Discharge regime. Sci. Total Environ. 793, 148564. https://doi.org/10.1016/j.scitotenv.2021.148564.
Salahi, A., Badrnezhad, R., Abbasi, M., Mohammadi, T., Rekabdar, F., 2011. Oily wastewater treatment using a hybrid UF/RO system. Desalination Water Treat. 28 (1–3), 75–82. https://doi.org/10.5004/dwt.2011.2204.
Sandoval, M.A., Coreño, O., García, V., Salazar-González, R., 2024. Enhancing industrial swine slaughterhouse wastewater treatment: optimization of electrocoagulation technique and operating mode. J. Environ. Manag. 349 (119556). https://doi.org/10.1016/j.jenvman.2023.119556.

Sarantinoudis, N., Tsinarakis, G., Dedousis, P., Arampatzis, G., 2023. Model-based simulation framework for digital twins in the process industry. IEEE Access 11, 111701–111714. https://doi.org/10.1109/ACCESS.2023.3322926.

Sengupta, P.K., 2018. In: Taberham, J. (Ed.), Industrial Water Management: Challenges and Opprtunities for Corporate Water Stewardship. John Wiley & Sons. www.bauer.de/bre.

Shang, W., Tiraferri, A., He, Q., Li, N., Chang, H., Liu, C., Liu, B., 2019. Reuse of shale gas flowback and produced water : effects of coagulation and adsorption on ultra filtration, reverse osmosis combined process. Sci. Total Environ. 689, 47–56. https://doi.org/10.1016/j.scitotenv.2019.06.365.

Sharma, M., Joshi, S., Prasad, M., Bartwal, S., 2023. Overcoming barriers to circular economy implementation in the oil & gas industry: environmental and social implications. J. Clean. Prod. 391, 136133. https://doi.org/10.1016/j.jclepro.2023.136133.

Sillanpää, M., 2020. Advanced water treatment: advanced oxidation processes. In: Advanced Water Treatment: Advanced Oxidation Processes. https://doi.org/10.1016/C2018-0-04453-9.

Smith, R.C., Sengupta, A.K., 2015. Integrating tunable anion exchange with reverse osmosis for enhanced recovery during inland brackish water desalination. Environ. Sci. Technol. 49, 5637–5644. https://doi.org/10.1021/es505439p.

Smol, M., Adam, C., Preisner, M., 2020. Circular economy model framework in the European water and wastewater sector. J. Mater. Cycles Waste Manag. 22 (3), 682–697. https://doi.org/10.1007/s10163-019-00960-z.

Swart, B., Pihlajamäki, A., John Chew, Y.M., Wenk, J., 2022. Microbubble-microplastic interactions in batch air flotation. Chem. Eng. J. 449, 137866. https://doi.org/10.1016/j.cej.2022.137866.

Syam Babu, D., Anantha Singh, T.S., Nidheesh, P.V., Suresh Kumar, M., 2020. Industrial wastewater treatment by electrocoagulation process. Separ. Sci. Technol. 55 (17), 3195–3227. https://doi.org/10.1080/01496395.2019.1671866. Bellwether Publishing, Ltd.

Teo, C.J., Karkou, E., Vlad, O., Vyrkou, A., Savvakis, N., Arampatzis, G., Dimakis, A.A., 2023. Life cycle environmental impact assessment of slaughterhouse wastewater treatment. Chem. Eng. Res. Des. 200, 550–565. https://doi.org/10.1016/j.cherd.2023.11.016.

Teo, C.J., Poinapen, J., 2021. The AquaSPICE conceptual water efficiency framework. Deliverable 4.1 of the EU-Funded Project "Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations (AquaSPICE).

The European Parliament and the Council, 2020. Regulation (EU) 2020/741 of the european parliament and of the council of 25 May 2020 on minimum requirements for water reuse. Off. J. Eur. Union L (Issue 177). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741&from=EN.

Trianni, A., Negri, M., Cagno, E., 2021. What factors affect the selection of industrial wastewater treatment configuration? J. Environ. Manag. 285, 112099. https://doi.org/10.1016/j.jenvman.2021.112099.

Tsui, T.H., Zhang, L., Zhang, J., Dai, Y., Tong, Y.W., 2022. Methodological framework for wastewater treatment plants delivering expanded service: economic tradeoffs and technological decisions. Sci. Total Environ. 823, 153616. https://doi.org/10.1016/j.scitotenv.2022.153616.

Valero, D., García-García, V., Expósito, E., Aldaz, A., Montiel, V., 2015. Application of electrodialysis for the treatment of almond industry wastewater. J. Membr. Sci. 476, 580–589. https://doi.org/10.1016/j.memsci.2014.11.007.

van Dijk, E.J.H., Pronk, M., van Loosdrecht, M.C.M., 2020. A settling model for full-scale aerobic granular sludge. Water Res. 186, 116135. https://doi.org/10.1016/j.watres.2020.116135.

Verhuelsdonk, M., Glas, K., Parlar, H., 2021. Economic evaluation of the reuse of brewery wastewater. J. Environ. Manag. 281, 111804. https://doi.org/10.1016/j.jenvman.2020.111804.

Walsh, B.P., Cusack, D.O., O'Sullivan, D.T.J., 2016. An industrial water management value system framework development. Sustain. Prod. Consum. 5, 82–93. https://doi.org/10.1016/j.spc.2015.11.004.

Wang, L., Liang, W., Chen, W., Zhang, W., Mo, J., Liang, K., Tang, B., Zheng, Y., Jiang, F., 2018. Integrated aerobic granular sludge and membrane process for enabling municipal wastewater treatment and reuse water production. Chem. Eng. J. 337, 300–311. https://doi.org/10.1016/j.cej.2017.12.078.

Wang, Q., Sheng, Y., Zhang, Y., Zhong, X., Liu, H., Huang, Z., Li, D., Wu, H., Ni, Y., Zhang, J., Lin, W., Qiu, K., Qian, X., 2024. Complete long-term monitoring of greenhouse gas emissions from a full-scale industrial wastewater treatment plant with different cover configurations. J. Environ. Manag. 360, 121206. https://doi.org/10.1016/j.jenvman.2024.121206.

Wang, S., Wei, J., Liu, Y., 2020. Development of an integrated aerobic granular sludge MBR and reverse osmosis process for municipal wastewater reclamation. Sci. Total Environ. 748, 141309. https://doi.org/10.1016/j.scitotenv.2020.141309.

Warren-Vega, W.M., Montes-Pena, K.D., Romero-Cano, L.A., Zarate-Guzman, A.I., 2024. Development of an artificial neural network (ANN) for the prediction of a pilot scale mobile wastewater treatment plant performance. J. Environ. Manag. 366, 121612. https://doi.org/10.1016/j.jenvman.2024.121612.

Wu, X., Yang, Y., Wu, G., Mao, J., Zhou, T., 2016. Simulation and optimization of a coking wastewater biological treatment process by activated sludge models (ASM). J. Environ. Manag. 165, 235–242. https://doi.org/10.1016/j.jenvman.2015.09.041.

Yang, S., Ma, K., Liu, Z., Ren, J., Man, Y., 2020. Development and applicability of life cycle impact assessment methodologies. In: Life Cycle Sustainability Assessment for Decision-Making: Methodologies and Case Studies. Elsevier Inc, pp. 95–124. https://doi.org/10.1016/B978-0-12-818355-7.00005-1.

Yetilmezsoy, K., Ilhan, F., Kiyan, E., Bahramian, M., 2022. A comprehensive techno-economic analysis of income-generating sources on the conversion of real sheep slaughterhouse waste stream into valorized by-products. J. Environ. Manag. 306 (114464). https://doi.org/10.1016/j.jenvman.2022.114464.

Yin, H., Guo, H., Qiu, P., Yi, L., Li, J., 2017. Case analysis on textile wastewater subjected to combined physicochemical–biological treatment and ozonation. Desalination Water Treat. 66, 140–148. https://doi.org/10.5004/dwt.2016.1619.

Zheng, H., Zhu, G., Jiang, S., Tshukudu, T., Xiang, X., Zhang, P., He, Q., 2011. Investigations of coagulation-flocculation process by performance optimization, model prediction and fractal structure of flocs. Desalination 269, 148–156. https://doi.org/10.1016/j.desal.2010.10.054.