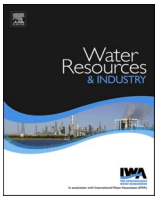
Water Resources and Industry 36 (2026) 100375



Contents lists available at ScienceDirect

Water Resources and Industry

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



Environmental assessment of a pilot-scale water recycling system for denim production

Mercè Font-Brucart [a,*], Christoph Studer [b], Cristian Blanco-Tirado [c], Marianny Y. Combariza [c], Michele Orlandi [d], Pinar Karagoz [e], Irwing Ramirez [e], Ajay Kumar [e], Satheesh Krishnamurthy [f], Jesús Cordón [g], Claudio Fernández-Acevedo [g], Samson Akanbi [h], Erdem Kestioglu [i], Tobias Walser [b], Roland Hischier [a]

[a] *Empa, Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory, Lerchenfeldstrasse 5, St. Gallen, 9014, Switzerland*
[b] *Vereala, Eyhof 34, Zürich, 8047, Switzerland*
[c] *School of Chemistry, Industrial University of Santander, Bucaramanga, 680002, Colombia*
[d] *Department of Physics, University of Trento, Via Sommarive 14, Povo, Trento, 38123, Italy*
[e] *The Open University, School of Engineering and Innovation, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom*
[f] *United Kingdom National Ion Beam Center, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom*
[g] *LUREDERRA, Foundation for the Technological and Social Development, Perguita Industrial Area, Calle A n. 1, Los Arcos, Navarra, 31210, Spain*
[h] *PCI Membranes, ul. Polna 1B, Kostrzyn, Wielkopolski, 62-025, Poland*
[i] *ULUCEV, Ulutek Teknopark, Bursa Uludag University, Görükle, 16059, Turkey*

ARTICLE INFO

Keywords:
Water recycling
Denim wastewater management
Renewable energy
Life cycle assessment
Environmental impacts

ABSTRACT

On-site treatment and recycling of denim wastewater represent an important opportunity to advance resource efficiency and reduce environmental burden of textile production. Because emerging treatment technologies can shift impact across the value chain, their evaluation requires a comprehensive life-cycle perspective. This study applies life cycle assessment to a pilot-scale water recycling system developed for denim manufacturing, integrating advanced oxidation processes, membrane treatment and photovoltaic-powered operation. Using data from the technology developers and modelled baseline scenarios, several optimisation pathways were explored. Results show that, relative to conventional wastewater treatment systems, the recycling system achieves lower impacts in water use and freshwater ecotoxicity categories by factors 5 and 50 respectively when recovering brine and operating solely on solar-derived electricity. Key contributing processes to the other assessed impacts are the consumption of chemicals during the operation stage and the manufacture of photovoltaic and battery components. The use of recyclable materials in energy components enhances overall system performance, allowing the system to counteract its impact on climate change and on nearly all the remaining impact categories. The findings highlight the importance of integrating resource recovery, renewable energy, and design-for-recycling principles to maximise the sustainability benefits of decentralised industrial water recycling systems.

* Corresponding author.
E-mail address: merce.fontbrucart@empa.ch (M. Font-Brucart).

https://doi.org/10.1016/j.wri.2026.100375
Received 17 March 2026; Received in revised form 28 May 2026; Accepted 7 June 2026
Available online 8 June 2026
2212-3717/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Ensuring water quality and availability is essential to achieving all Sustainable Development Goals (SDGs), either directly or indirectly. However, at a global scale, the planetary boundaries for water have already been exceeded [1]. Water scarcity and pollution are being further aggravated by climate change and the loss of biodiversity [1,2]. While this global challenge requires multifaceted solutions, water recycling is recognised as a key strategy to reverse the current trend [1,2].

Water recycling initiatives are expanding worldwide [3] and are expected to grow further under evolving national and international water policies. At the international scale, the integrated monitoring initiative for SDG 6 —which aims to guarantee clean water and sanitation for all— emphasises the need to monitor the proportion of domestic and industrial wastewater that is safely treated [4]. Moreover, climate-resilient water safety planning is essential to ensure safe drinking water supplies [5].

In Europe, the Water Framework Directive [6] provides the overarching structure for water policy, supported by the Drinking Water Directive [7], the Urban Wastewater Treatment Directive [8] and the Regulation on Minimum Requirements for Water Reuse [9]. Together, these frameworks apply risk assessment methodologies to enable the safe and sustainable use of water according to its intended purpose.

While water policies can broadly promote water recycling, the adoption of recycling practices within industry can be further strengthened through international and European corporate sustainability policies and regulations. Industry has the duty of managing natural resources responsibly and applying measures at the source to prevent and control pollution [10–12]. In addition, industrial activities impacting most on the environment need to obey sectorial policies. This is the case of the textile sector, which needs to reduce the environmental impact of their activity and products to meet the targets set by 2030 by the European Union [13]. To reach these targets, the adoption of improved water management practices can play a major role.

Within the textile industry, denim represents one of the most significant global subsectors and traditionally has been associated with considerable negative impacts both on human health and the environment [14]. Current strategies to improve the environmental performance of the denim life cycle focus on three main areas: (1) the use of more responsibly sourced fibres —such as organic or recycled cotton and alternative biobased fibres; (2) the improved management of chemicals including reducing their use and substituting hazardous substances with safer alternatives; and (3) the treatment and recycling of denim wastewater [15], [16,17].

Currently, the most common technique applied to treat textile wastewater is the aerobic biological process with activated sludge, which is not efficient in removing textile pollutants from water [18]. State-of-the-art techniques for dyeing with typical denim dyes such as vat dyes and reactive dyes result in wastewater containing unfixed dye and a variety of additives used in the dyeing process comprising both organic and inorganic compounds [17–19]. Although some denim dyes such as indigo can be synthesized biologically, conventional dyes are not biodegradable under the conventional biological wastewater treatment conditions or in aquatic ecosystems [18,20]. Salts constitute a main group of inorganic compounds that are added into dyeing baths to adjust the chemical structure of the specific dye to be applied [18,21,22]. Several alternative dyeing techniques that aim to reduce chemical and salt usage have been investigated but have not yet achieved commercial scale implementation [23,24]. Additionally, vat and reactive dyes can contain metals and hazardous organic compounds as impurities [25,26]. Fibres are also present in denim effluents. Although cotton is the most important textile fibre used for denim manufacture, polyethylene terephthalate is also being employed [27]. While natural fibres like cotton can be degraded by oxidation processes, synthetic fibres are more efficiently separated from water by filtration processes [28–30].

Within the Horizon 2020 project “Waste2Fresh”, a consortium of 17 international partners developed a novel treatment train capable of degrading dyes commonly employed in denim manufacturing and scaled this up to the pilot scale level, with ongoing research focused on brine recovery. Furthermore, the innovative system is powered by solar energy —i.e. solar photovoltaic (PV) electricity, and solar concentration and photocatalysis for pollution abatement. The pilot plant reached a technology readiness level (TRL) close to 7 at the project conclusion, which represents the culmination of extensive testing of different combinations of advanced treatment technologies.

An essential element in the design of a water recycling plant is a comprehensive monitoring plan that, based on the risk assessment framework, ensures both the proper performance of all treatment stages and compliance of reclaimed water quality with the intended end-use requirements [5,9,31]. For water recycling projects targeting industrial or technical applications, it is equally critical to demonstrate not only compliance with health and safety requirements but also that the proposed scheme delivers measurable environmental benefits compared to the current practice. In this context, the life cycle assessment (LCA) methodology provides an appropriate analytical framework, as it offers a systematic evaluation of environmental impacts and can integrate safety considerations into technology development [32,33]. Within Europe, the Safe and Sustainable by Design (SSbD) Strategy recommends the application of the LCA methodology to analyse the environmental sustainability of chemicals and materials that are newly designed, with increasing detail as their development reaches more advanced innovation stages [34].

In previous studies, LCA was already applied to assess potential technologies to treat textile brine for resource recovery [35–37]. The novelty of the present LCA analysis lies in considering a set of water quality indicators to assess water quality according to its further intended use. This work builds on this main design principle to analyse the complete treatment process proposed within the Waste2Fresh project and estimate its environmental benefits to support its further development. Consideration of the social and economic dimensions of sustainability will also be essential to ensure the successful implementation and scalability of these new, decentralised water recycling systems [38].

2. Materials and methods

The goals of the present LCA study are (1) to assess the environmental impacts of the Waste2Fresh denim wastewater treatment system (in the following referred to as the Waste2Fresh System, W2F) in comparison with a conventional denim wastewater treatment system (in the following referred to as the Conventional System, CS), and (2) to help prioritise possible improvement strategies.

To make the Waste2Fresh System and the Conventional System comparable, the following functional unit (FU) was applied: "A provision of 14600 m^3 water for washing and dyeing, with the condition that treated water meets the requirements for its intended use". This volume of water represents the annual flow rate (i.e., 40 m^3/day, 365 day/year) calculated based on the design flow rate of the current pilot plant of the textile company Erak (Turkey), implementation partner of the Horizon 2020 project. Compliance with the water use quality requirements means thereby specifically: (1) in the Conventional System, the effluent complies with the required standards for discharge to the environment; (2) in the Waste2Fresh System, the fraction of reclaimed water satisfies the technical and human health requirements for washing and dyeing, while the brine meets the required standards for discharge.

The main foreground data was collected via surveys from the technology partners within the Waste2Fresh project (Table 1). Literature data was used to model the missing foreground processes. The background data was taken from the ecoinvent database [42] (version 3.10, cut-off model) (see section S3). The Environmental Footprint method [43] (EF method) was applied to conduct the impact assessment. The LCA software SimaPro [44] (version 9.6) was used to access the above-mentioned data required for modelling. For potential leaching of nanoparticles from the applied nanomaterials, characterisation factors (CFs) for the toxicity impact categories according to the USEtox [45] approach were determined (see sections 2.3 and 2.4). An additional analysis based on the grey water footprint (grey WF) concept [46] was conducted to complement the information obtained from the water use and freshwater impact categories determined according to the EF method (see section S5.2).

2.1. Examined systems

Figs. 1 and 2 show the system boundaries of the Conventional System and the Waste2Fresh System respectively.

The Conventional System —which is based on the treatment scheme currently in place at the textile company where the pilot plant was built— integrates the following series of technologies: (1) filtration of coarse particles via screening and flow equalisation, (2) pH neutralisation, (3) coagulation-flocculation, and (4) aerobic biological treatment with activated sludge. The treated water is then discharged to a local river, while the sludge is first dried on site by mechanical means, and afterwards it is transferred to an incineration plant. This treatment system can be considered state-of-the-art [18,47]. The inventory data required to model the Conventional System (i.e., data on chemical and energy consumption and on sludge management), however, was only partially covered by primary sources and literature data was used instead.

The concept of the Waste2Fresh System analysed in this study comprises the following technologies: (1) filtration of coarse particles via screening and flow equalisation; (2) advanced oxidation process (AOP) of dyes via a Fenton-like process which uses a nano-magnetite catalyst that is supported by fibres from fique, a native Colombian plant (nano-Fe_3O_4-fique treatment); (3) nanofiltration to separate divalent ions and organic compounds from the wastewater stream; (4) heterogeneous photocatalysis with nanoscale graphitic carbon nitride (gC_3N_4) to oxidise organic compounds in the concentrate produced by nanofiltration; (5) solar concentration-driven AOP to treat the concentrate further; (6) ion exchange with a polyamidoamine–cyclodextrin (PAA-CD) cross-linked copolymer resin to remove metals from the water supply; (7) rainwater harvesting to replace water losses from the system; and (8) silicon PV electricity generation to run the equipment during the day. The PV system is integrated on the roof of the factory.

The combination of water treatment technologies results in multiple barriers that allow meeting all the technical requirements for recycling the reclaimed water on site but not yet the concentrate or retentate fraction. The retentate complies with the local standards for discharge when electrocoagulation (EC) is applied before photocatalysis. Experimental work conducted so far has shown that both indoor photocatalysis and solar concentration benefit from the presence of residual hydrogen peroxide in the concentrate, which is firstly used in the upstream nano-Fe_3O_4-fique process.

Table 1
Technology developers and sources of the foreground data used in this study.

Technology	Technology developer/Foreground data source
Nano-Fe_3O_4-fique catalysis	Industrial University of Santander (UIS)
Nanofiltration	PCI Membranes
Solar concentration-based AOP	University of Trento (UNITN) [39]
Electrocoagulation and gC_3N_4-photocatalysis	The Open University (OU)
Ion exchange with PAA-CD-based resin	LUREDERRA
Rainwater harvesting system	Centre for Sustainable Development and Innovation of Water Technology of Norway (CSDI)
Nanobubble technology	NANOGENTECH (technology under development, not included)
Electrochemical biological sensors	Institute of Molecular Biology and Genetics of Ukraine (IMBG) [40,41] (technology not included)
Photovoltaic electricity system	ULUCEV, UNITN
Process scale-up	Centre for Process Innovation (CPI), technology developers
Water quality data at the feed and along the treatment train on the pilot scale	Project partners, Konya Technical University (KTUN)

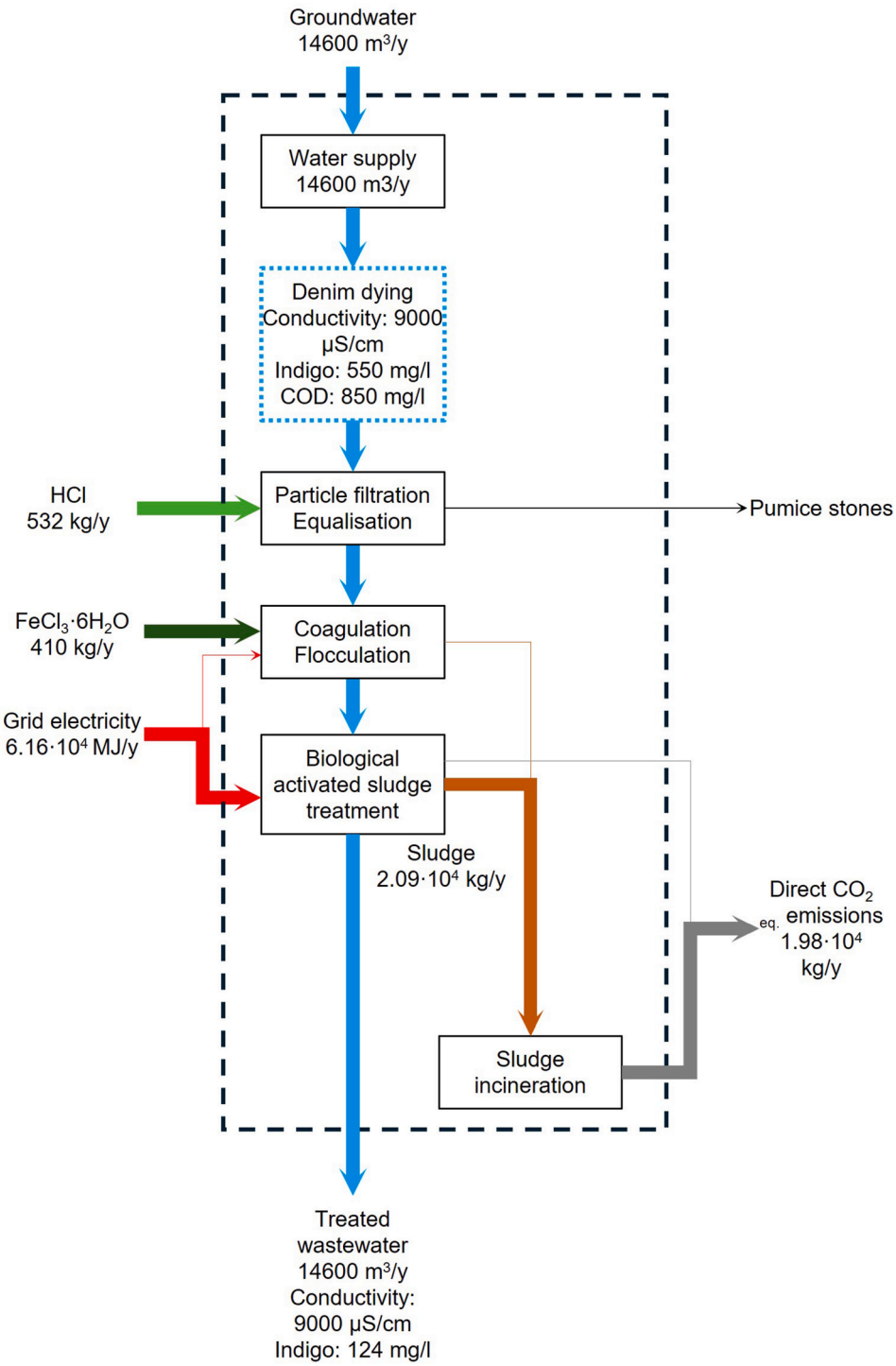


Fig. 1. Conventional System boundaries.

Currently, the layout of the pilot plant does not include a treatment process for the washing wastewater that originates from the daily cleaning of the nanofiltration membrane (cleaning-in-place system, CIP). Even though a fraction of the permeate can be used to clean the membrane, an equivalent amount of freshwater needs to be used to comply with the functional unit requirements. Rainwater can supply this demand if it is available. Otherwise, groundwater is used (see section 2.3).

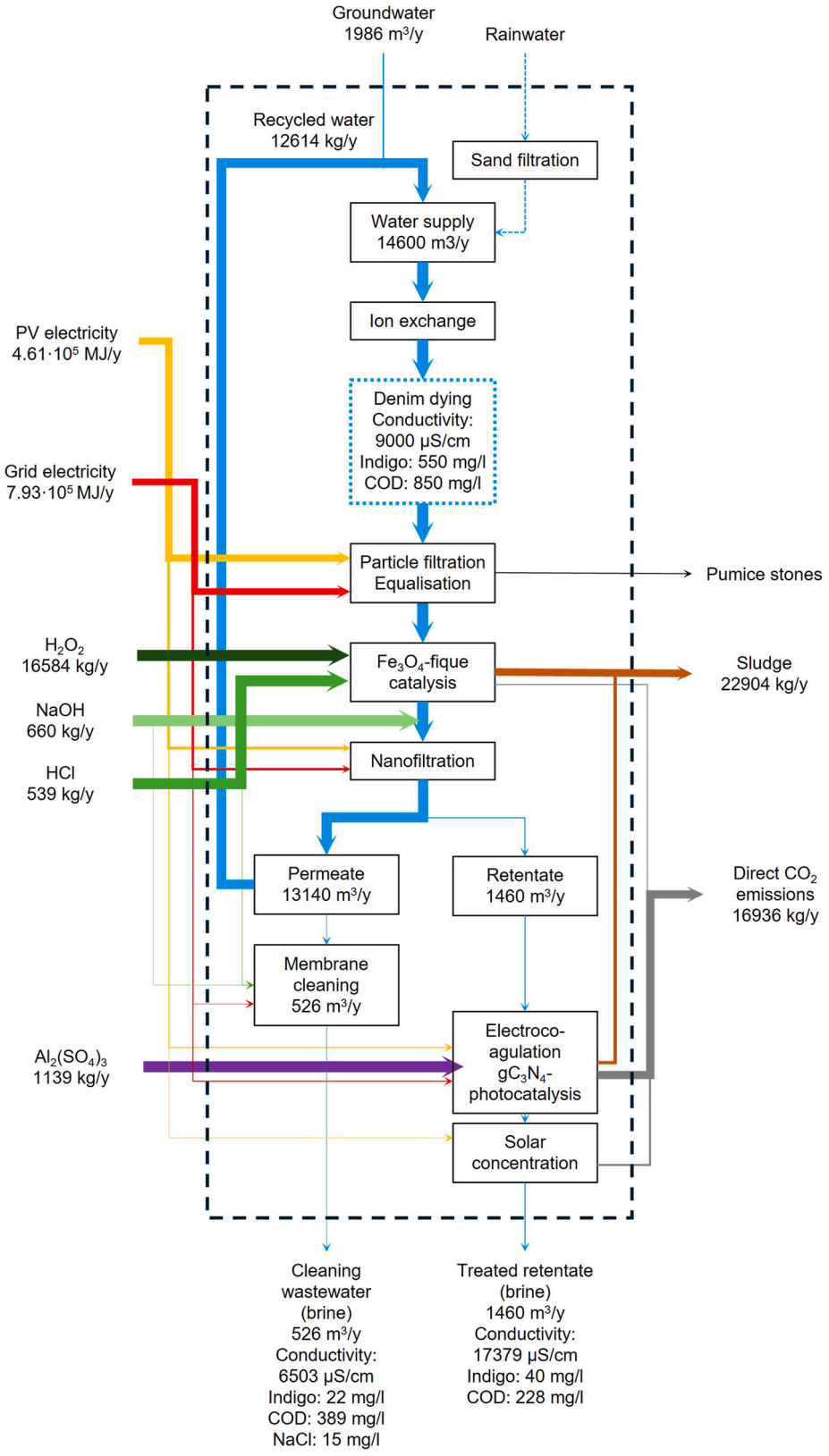


Fig. 2. Waste2Fresh System (W2F-Bas0 scenario) boundaries.

2.2. Water quality evaluation

Assessment of the reclaimed water quality was based on the consideration of the following set of chemical indicators and surrogate parameters: indigo, electrical conductivity, arsenic and copper (Table 2). The main criterion for their selection is their representativeness of the diversity of the main groups of components that may be present in a denim effluent (dyeing and washing activities) and that thus may behave and interact differently with each of the assessed technologies, criterion which is closely linked to the application of the multibarrier approach to water treatment [31,57]. A more detailed justification of the selection of this set of indicators is provided in section S2.

Water quality values that are likely to be protective of freshwater ecosystems were assigned to these indicators. To suggest the freshwater quality targets, the environmental quality standards set by the Turkish Regulation on Surface Water Quality (TRSWQ) [56] —which integrates the environmental quality standards established by the European Water Framework Directive— were considered for those indicators that are regulated. To complement the data provided by the standards and to provide reference values for unregulated indicators, water quality criteria from international and European guidelines and additional literature data were analysed (see section S2).

2.3. Examined scenarios

Criteria based on the principles of green chemistry [58] and the framework of the R-strategies [59] were applied to collect and analyse data for a total of 6 different scenarios studied for the Waste2Fresh System, 3 baseline and 3 optimised scenarios (Table 3).

For the Waste2Fresh System reference baseline scenario, W2F-Bas0 (which corresponds to Fig. 2), data on the laboratory and pilot scales of each water treatment technology was considered. Data on the consumption of resources required to synthesise the main components and to operate the technologies was compiled, without considering the management of the materials or the solutions at the end of their life. Only incineration of the membrane materials was included since membrane-based technologies are already on a commercial scale and incineration is a main final treatment [60].

Within the group of baseline scenarios, two additional scenarios were built, which only differ slightly from scenario W2F-Bas0. Scenarios W2F-Bas1 and W2F-Bas2 represent a best and a worst-case respectively to account for the risk of emitting nanoparticles during the production stage of nanocatalysts. Data on migration of nanoparticles to water and air during the manufacturing and operating stages of the corresponding catalysts was not available. Because of this, together with the fact that very limited toxicological and ecotoxicological data was found for gC_3N_4 in the literature, it was not possible to determine CFs for gC_3N_4, and the analysis of nanomaterials was limited to the estimation of potential Fe_3O_4 emissions occurring during the synthesis process (see section 2.4 below, and section S4 for additional methodological aspects, and the toxicological and ecotoxicological information used for the calculation of effect factors (EFs) and CFs). More details on the baseline scenarios can be found in section S3.1.

Within the group of optimised scenarios, several strategies were analysed to optimise the environmental performance of the complete train at industrial scale. Within scenario W2F-Opt1, a process alternative to electrocoagulation to remove DOM based on granular activated carbon adsorption was assumed to be applied after Fe_3O_4-fique treatment to reduce sludge formation and facilitate the performance of downstream processes. The concentrate treated by photocatalysis and solar concentration as well as the brine generated by the membrane CIP system were assumed to be further treated by bipolar membrane electrodialysis (BMED) units to recover acid, base and diluate fractions. Also, in the same scenario W2F-Opt1, the gC_3N_4-based catalyst was assumed to be synthesized in a process with recovery of the reagents: in a hydrothermal process with recovery of the water and ammonia, or in a process without water (pyrolysis) and without the use of ammonia salts. Moreover, urea was considered as precursor of this carbon-based catalyst, since it is not toxic in comparison with other commonly applied precursors such as melamine, cyanamide and dicyanamide [61,62]. Data on the environmental profile of commercial urea [42], which is derived from synthetic ammonia, was used in this analysis, though, urea might be potentially obtained from other more environmentally friendly routes [63]. Additionally, the water used to wash the Fe_3O_4-fique catalyst during the synthesis stage was assumed to be treated for recovery. Finally, in scenario W2F-Opt1, it was assumed that all the electricity required to operate the plant and to synthesise the Fe_3O_4-fique catalyst and gC_3N_4-photocatalyst is generated onsite by a PV installation coupled with a LFP battery system. Fig. 3 shows a flow diagram corresponding to scenario W2F-Opt1.

Within scenarios W2F-Opt2 and Opt3, additional measures aimed to improve the sustainability of the supply chains of the energy-

Table 2
Environmental standards and water quality criteria considered.

Indicator	Unit	Target	Reference
Indigo	µg/l	10	[48,49]
Conductivity	µS/cm	400-1000	TRSWQ
		300-1000	[50,51]
As, total	µg/l	53	TRSWQ
		1-47	[52–55]
Cu, total	µg/l	21	TRSWQ
		1.4-9.5	[52,55]

TRSWQ: Turkish Regulation on Surface Water Quality [56]

Table 3
Overview of the Waste2Fresh System scenarios.

Group	Name	Main considerations
Baseline scenarios	W2F-Bas0	Consideration of the main aspects of the technologies developed during the project.
	W2F-Bas1	Consideration that low emissions of Fe_3O_4 nanoparticles occur during the manufacture of the nano-Fe_3O_4-fique catalyst.
	W2F-Bas2	Consideration that high emissions of Fe_3O_4 nanoparticles occur during the manufacture of the Fe_3O_4-fique catalyst.
Optimised scenarios	W2F-Opt1	Consideration that the solutions from catalyst manufacture, the concentrate from nanofiltration, and the cleaning solutions from the membrane CIP system are treated for resource recovery; the supply of electricity comes exclusively from a silicon PV installation coupled with a lithium iron phosphate (LFP) battery system; and a process for dissolved organic matter (DOM) adsorption based on activated carbon is applied after Fe_3O_4-fique treatment.
	W2F-Opt2	The same considerations as those applied to scenario Opt1 plus consideration that PV modules and the LFP battery are built from recycled materials (flat glass, silicon and copper in PV modules; and aluminium, copper and LFP-containing materials in the battery), and regenerated activated carbon is used for DOM removal.
	W2F-Opt3	The same considerations as those applied to scenario Opt2 plus consideration that distributed silicon photovoltaic electricity sources produce the electricity required to produce PV modules and the battery system.

related components and activated carbon were considered. More details on the optimised scenarios can be found in section S3.2.

2.4. Derivation of characterisation factors for nanomaterials

For nanoscale Fe_3O_4, relevant in-vivo data was found and nanospecific EFs for human health and the environment were calculated (Table 4). Data on releases of Fe_3O_4 nanoparticles during the production of the nano-Fe_3O_4-fique catalyst was not available. Therefore, best- and worst-case estimations for environmental exposure (see Supplementary Table 34 in section S4.3) and human intake (see Supplementary Table 35) were made to derive CF values. At least, with this approach, the relevance of Fe_3O_4 releases to the overall LCA results can be shown.

3. Results and discussion

Fig. 4 shows the life cycle assessment results obtained for six impact categories: climate change (CC), water use (FwU), freshwater ecotoxicity (FwE), marine eutrophication (ME), mineral and metal resource use (MMRU), and non-cancer human toxicity (nCHT). The impact scores were calculated relative to the highest impact score obtained in a specific impact category. These impact categories were selected since they are those most directly affected by the foreground processes considered within the Waste2Fresh System, and at the same time, they are representative of the pattern shown by the analysis of the remaining impact categories (see Supplementary Table 38). Figs. 5 and 6 show the contributions of the analysed processes to the impact categories in scenarios W2F-Bas0 and W2F-Opt1 respectively. To ease their interpretation, the results are discussed separately according to main environmental aspects.

3.1. Water- and toxicity-related impacts

In this section, the results obtained in the FwU, FwE and nCHT impact categories are described. The FwE impact category is affected by direct emissions of water quality indicators to freshwater during the operation stage of the systems under investigation, while the nCHT impact category is affected by emissions of nanoparticles during the synthesis of catalysts.

In the FwU impact category, Fig. 4 shows that all Waste2Fresh scenarios perform better than the Conventional System. The contributions of the W2F baseline scenarios to this impact category are a factor 2 lower than those of the Conventional System, and the W2F optimised scenarios are a factor 5 lower (see Supplementary Table 39). In contrast, in the FwE impact category, only the W2F optimised scenarios obtain impact scores that are lower than those of the Conventional System by a factor about 50 (scenario W2F-Opt1) to 70 (scenarios W2F-Opt2, Opt3). The results obtained in the FwE impact category agree with those determined by applying the grey WF concept. While the grey WF of scenario W2F-Bas0 is about a factor 30 lower than that of the Conventional System, the grey WF values of the optimised scenarios are a factor 10^5 (5 orders of magnitude) lower than that of the Conventional System and lower than the overall domestic demand estimated for the basin under study in 2015 [64] by a factor 10^5 too (see Supplementary Table 37).

The FwE impact category and the grey WF parameter complement each other as regards the impact of discharging brine in scenario W2F-Bas0. In deriving CFs for the water quality indicators according to the USEtox method, where EFs are normalised to effect concentrations, no natural dilution effect was considered. Apart from natural dilution, the water quality indicators used in the present study cannot be attenuated readily by biodegradation or direct photolysis in natural aquatic ecosystems [20,65,66]. The contribution to the FwE impact category is the result of aggregating the mass flows of indigo and the metal indicators without considering conductivity. Conductivity was used as a surrogate parameter for salts. While CFs for salts emitted into freshwater ecosystems are in the process of being developed under the USEtox model [67], the grey WF concept is applicable to all water quality indicators, including conductivity. However, the grey WF parameter reflects the maximum dilution volume required to meet all the quality targets defined in Table 2.

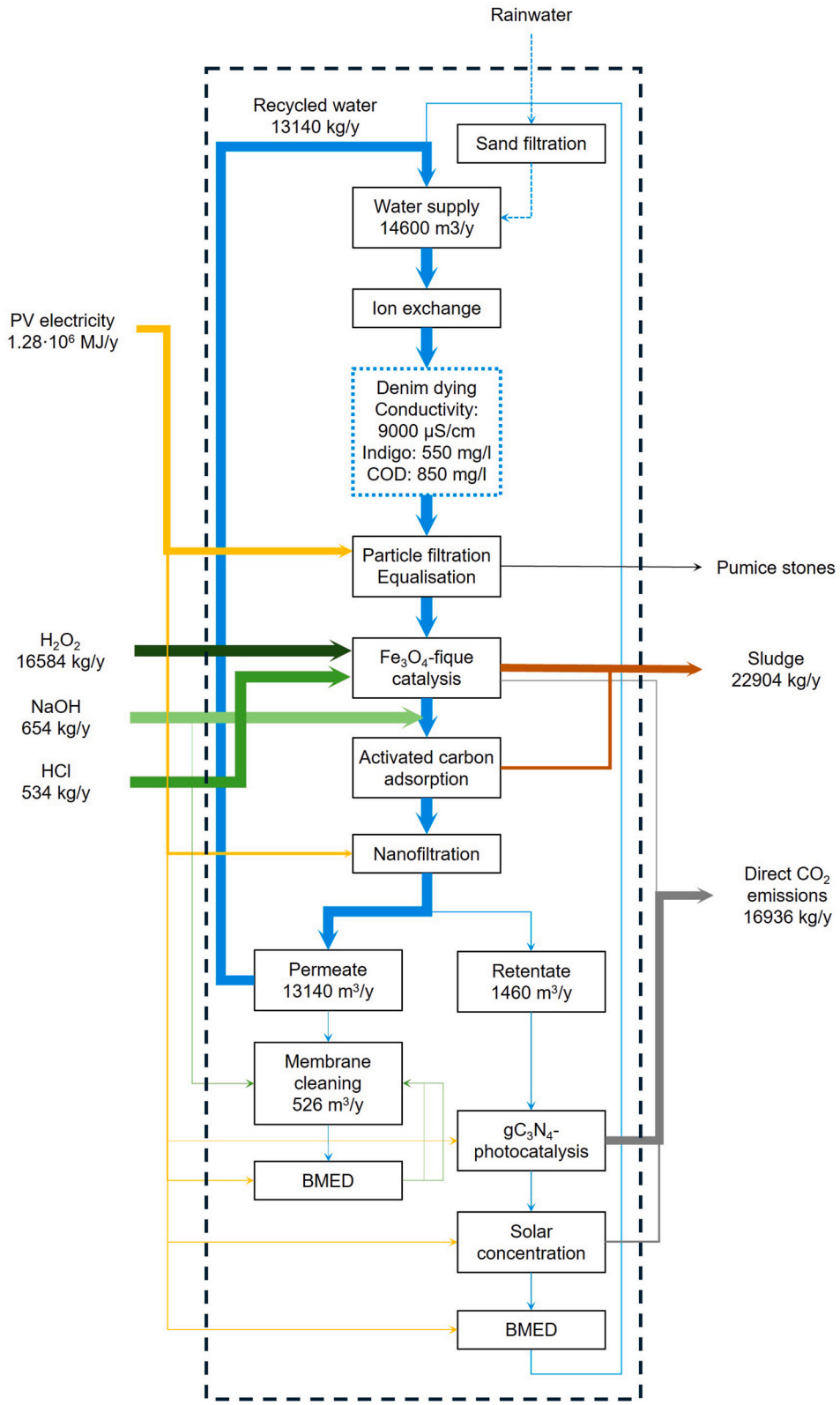


Fig. 3. W2F-Opt1 scenario boundaries.

Table 4
EFs for nanoscale Fe_3O_4.

EF ecotoxicology, freshwater	EF human, non-cancer, inhalation	EF human, non-cancer, oral uptake
PAF m^3/kg emitted	cases/kg intake	cases/kg intake
31	2.5	0.38

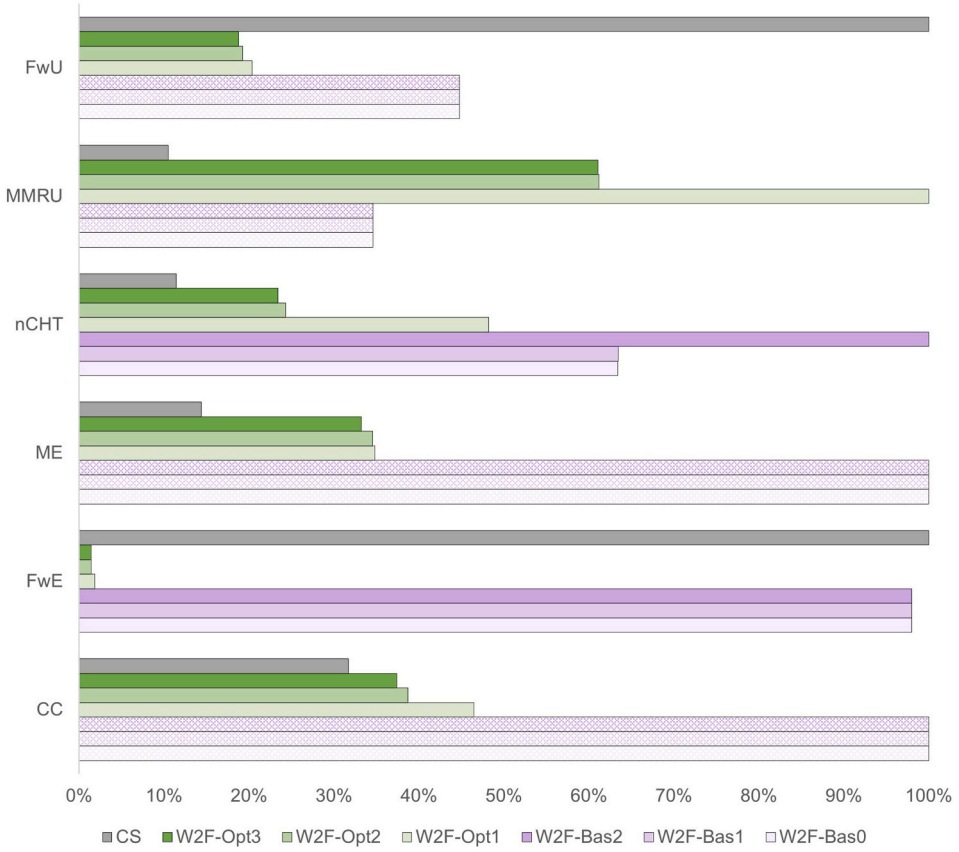


Fig. 4. Impact score (%) obtained by each scenario relative to the highest impact score calculated for each specific impact category: climate change (CC), freshwater ecotoxicity (FwE), marine eutrophication (ME), non-cancer human toxicity (nCHT), mineral and metal resource use (MMRU), and water use (FwU). Equal percentages are indicated with a pattern.

In the nCHT category, Fig. 4 shows that consideration of high emissions of Fe_3O_4 nanoparticles during the catalyst synthesis (scenario W2F-Bas2) translates into an increase of the score that is about a factor 2 higher than that of scenario W2F-Bas0. In the optimised scenarios, no special measures were integrated to control human exposure to nanoparticles Therefore, although not shown in Fig. 4, if high migration rates of nanoparticles occurred, the Waste2Fresh System would perform worse in the optimised scenarios in this impact category too. Further measurements will need to be conducted to determine if migration of nanoparticles from the catalysts occurs with the final goal of establishing measures to prevent or minimise this process.

A last aspect of the Waste2Fresh System on water use and on toxicity impacts is related to the management of the metal-containing solution obtained after regenerating the ion exchange resin. This spent solution should be treated for the recovery of the metals. Separate recovery of the metals should be feasible, e.g. by adjusting the leaching conditions through the ion exchange resin [68]. Special management measures should be taken for arsenic. Even when this metalloid is handled properly (i.e., in semiconductor-related applications), its management becomes more complex due to its toxicity and the fact that, if released into the environment, it can be transformed into highly mobile species (i.e., methylated arsenic) [69–71]. Overall, measures to prevent arsenic from migrating from any containment media should be implemented.

3.2. Energy-related impacts

In scenario W2F-Bas0, the overall consumption of electricity (from grid and the onsite photovoltaic system) has a dominating influence on all impact categories except on FwE (Fig. 4). As shown in Fig. 2, the most electricity-consuming processes are the heating

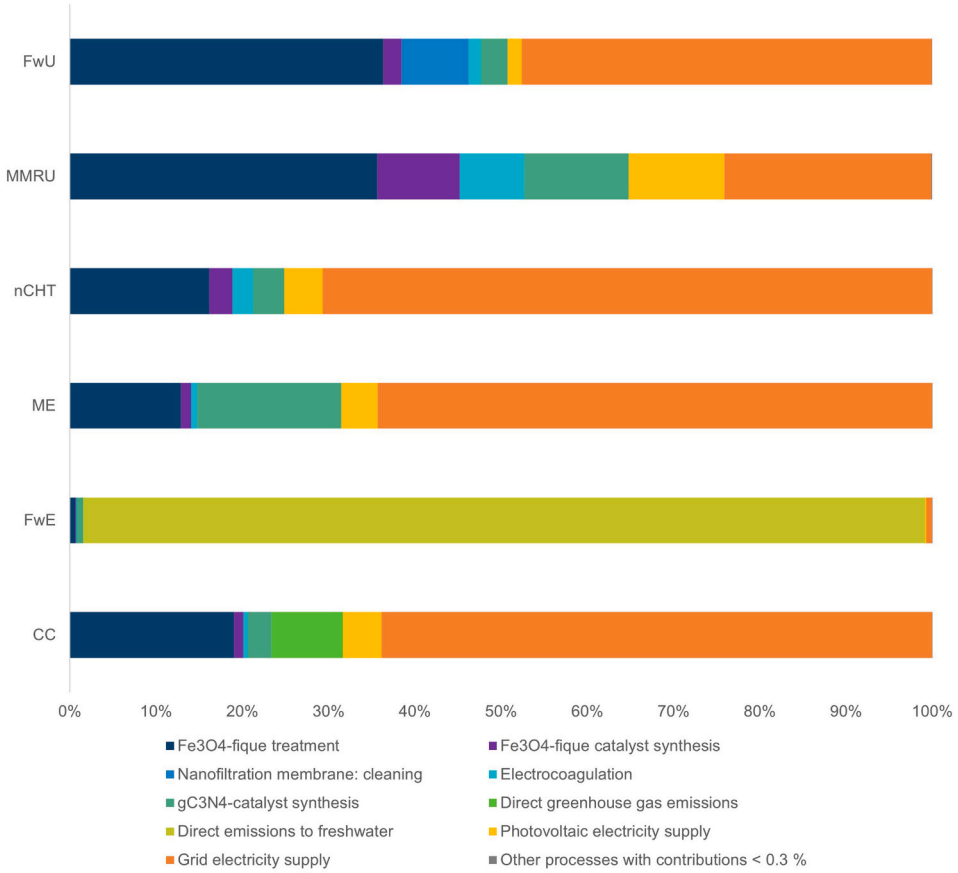


Fig. 5. Contribution of each process assessed to the overall score obtained by scenario W2F-Bas0 in a specific impact category. The abbreviations used for the impact categories are explained in Fig. 4.

of wastewater for nano-Fe_3O_4-fique catalysis (thermal energy storage), the pressure-driven membrane separation, and the LED lighting system for indoor photocatalysis.

In the optimised scenarios of the Waste2Fresh System, no dedicated measures were considered to reduce the energy consumption of these processes. But to scale up the treatment plant, it will be necessary to study possible energy reduction measures at the design and operation stages of these processes more closely. This analysis should be conducted in an integrative way. For example, measures aimed to reduce the likelihood of fouling of the membrane surface and lower the maintenance requirements of this technology might contribute to lower the overall energy requirements. Also, it will be possible to reduce reliance on the use of LEDs for photocatalysis once the efficiency of gC_3N_4-photocatalyst has been proven.

The gC_3N_4-photocatalyst is active under visible radiation, and therefore, reducing reliance on the use of LEDs can be achieved by continuing investigating the combined application of photocatalysis and solar concentration, and by employing LEDs that generate photon fluxes closer to the wavelengths where they are most efficient. Initial tests where both solar concentration and photocatalysis were applied already showed the high efficiency of such a combination of technologies for dye degradation. Outside the band of wavelengths where LEDs are most efficient (about 460 nm), they generate notably lower photon fluxes, and a higher number of them needs to be used to generate the number of photons required for a certain photochemical process [72]. Previous LCA studies already showed the influence of the electricity consumption on environmental impacts when UV-LEDs were used to drive reactions with UV-absorbing photocatalysts [73,74], and how the use of gC_3N_4-photocatalyst might contribute to reducing electricity requirements [75].

Besides their impact on energy consumption, the impact of LED production also must be accounted for. In the present study, only an approach to the synthesis of gallium nitride, which is a main constituent in current inorganic LEDs [76], was included. Current GaN production by chemical vapour deposition is not efficient in terms of the small fraction of ammonia-precursor transformed into the GaN film [77]. Besides gallium (with trimethylgallium as precursor), other metals and critical materials are used to produced LEDs [78, 79]. Research is being conducted to develop recycling technologies for LEDs [79–81] as well as to develop other semiconductors for LEDs like zinc oxide [82].

The amount of electricity consumed to synthesise the two catalysts represent a minor fraction relative to the overall amount of electricity consumed in scenario W2F-Bas0 (lower than 0.5 % relative to the functional unit). Also, they represent lower contributions

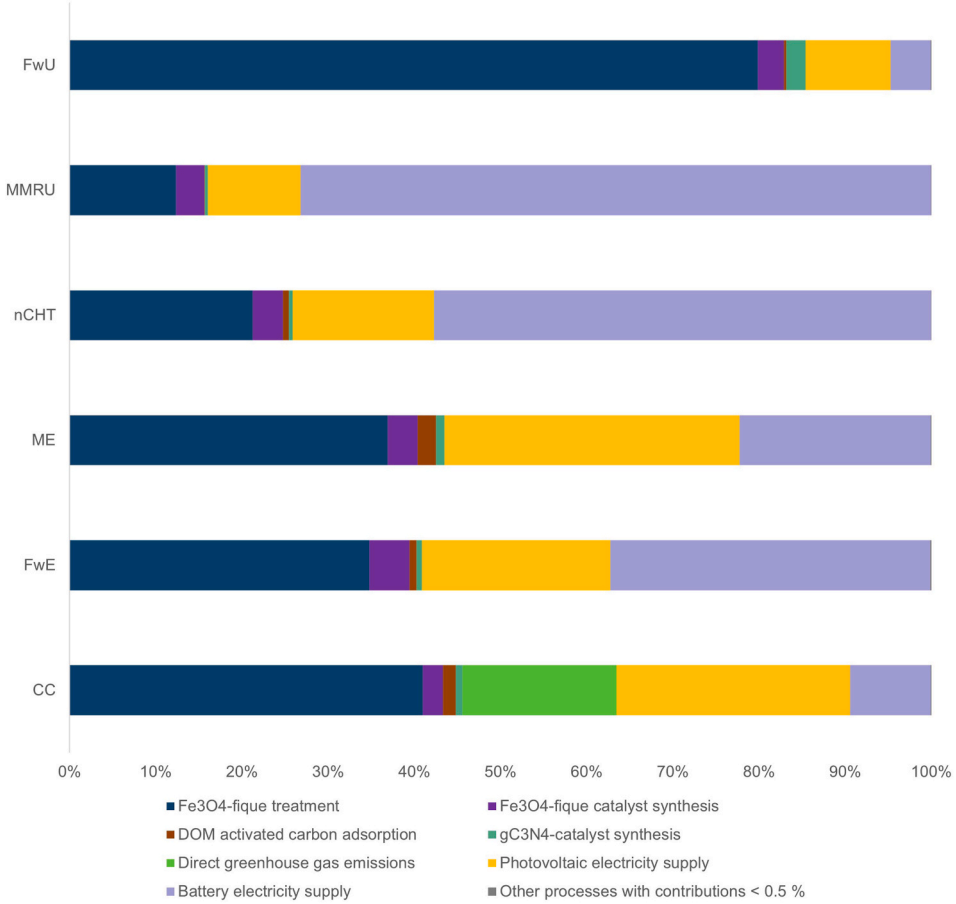


Fig. 6. Contribution of each process assessed to the overall score obtained by scenario W2F-Opt1 in a specific impact category. The abbreviations used for the impact categories are explained in Fig. 4.

to the overall impacts estimated for the corresponding synthesis processes (lower than 23°% for Fe_3O_4-fique catalyst and lower than 6°% for gC_3N_4-photocatalyst). About the synthesis of gC_3N_4-photocatalyst, this result differs from a previous study [75], in which the consumption of electricity contributed most to the environmental impacts.

Even though recovery of brine flows would involve increasing the consumption of energy, consideration that all the consumed electricity might be supplied from solar sources (scenario W2F-Opt1) contributes to reducing most impacts, except in the MMRU category, relative to the scores achieved in scenario W2F-Bas0 (e.g., a reduction factor 4 in the CC category is achieved). Production of PV modules and the battery system contribute most to the MMRU impact category (Fig. 6). An electricity consumption for BMED of about 3.3 kWh/m^3 treated water, without including pumping requirements, was considered in the optimised scenarios based on previous studies (see S3.2.2). Application of this technology can be advantageous for treating brine containing salts (e.g., NaCl) in concentrations up to about 1-2°M [83–85]. Although it has been shown that this technology might be applied for dye-containing brine [83], the concentrations of dye molecules and other dissolved organic matter should be low in the feed to minimise membrane fouling [85,86]. Therefore, to investigate the suitability of these technologies for the Waste2Fresh System further, it will be necessary to characterise wastewater with regard to the composition of salts and dissolved organic matter in more detail from the feed point.

In scenarios W2F-Opt2 and W2F-Opt3, measures aimed to build more circular supply chains of the PV and the battery systems help to further decrease the scores in all impacts (see Supplementary Table 38).

3.3. *Chemical-related impacts*

Fig. 5 shows that the synthesis of the catalysts and the consumption of chemicals for Fe_3O_4-fique treatment and electrocoagulation during the operation stage have considerable contributions to the overall scores obtained in scenario W2F-Bas0 in most impact categories (from 23°% in CC to 65°% in MMRU categories). In the optimised scenarios, the contributions of the use of chemicals decrease most notably in the FwE and ME impact categories (reduction factors of about 2).

Consumption of hydrogen peroxide is the major contributing process to the impact scores of the Fe_3O_4-fique treatment in the baseline and optimised scenarios (Figs. 5 and 6), but it is necessary to add that residual amounts of this product is of benefit to

downstream advanced oxidation processes too. Previous studies also indicated that the consumption of chemicals has an important impact on the overall scores attained by Fenton-based oxidation processes [87,88].

Regarding gC_3N_4-photocatalyst synthesis, it is the use of ammonium chloride that contributes most to the impacts scores. Notable reductions of the scores of this synthesis process are achieved in the optimised scenarios, where the ammonia salt is assumed to be recovered (or its use can be avoided). Although the requirements needed for this recovery were not analysed in detail, significant overall reductions might be expected, especially in the FwE and ME impact categories, where savings in this chemical represent reductions larger than one order of magnitude with respect to the scores of the synthesis process obtained in scenario W2F-Bas0.

About electrocoagulation, an alternative process for dissolved organic matter removal after Fe_3O_4-fique treatment was suggested consisting of activated carbon adsorption. Only under the consideration that regenerated activated carbon is used (scenario W2F-Opt2), this alternative treatment helps to significantly reduce the respective impact scores (reduction factors between 6 and 9 relative to those achieved in scenario W2F-Opt1). Despite this suggestion, however, the composition of organic matter (e.g., content of oxidation byproducts, biodegradable OM or residual fibres) will need to be better characterised before deciding on a technology alternative to electrocoagulation.

Lastly, it is of note that, besides the possible measures considered in the optimised scenarios, research is being conducted to synthesise a Fenton-like catalyst that can work at neutral pH so that the need to acidify the water can be avoided.

3.4. Design of technology materials

In this section, the technology materials developed within the project are qualitatively assessed regarding the design-for-recycling principle. The end of life of the new materials was not fully evaluated in the LCA analysis. Disassembly and recycling of most materials at the end of their life should be possible, although more testing is yet to be performed. As it may be inferred from the LCA results, the overall impacts of the Waste2Fresh System would decrease further when the use of recycled materials within the system increased.

Specifically, for the nanocatalysts, it should be ensured that their components can be safely separated at the end of their life, so that the nanocatalyst as well as its substrate materials can be recycled or conveniently treated (for example, the fique fibres can be composted).

The PAA-CD-based ion exchange resin was studied in combination with a lower fraction of polystyrene-divinylbenzene to enhance the efficiency of the resin to remove arsenic from water. Since chemical recycling of other related polymers (i.e., polyamides and polystyrenes) is being tested at the laboratory or pilot scale [89], it seems reasonable to suggest prioritising the use of the biobased resin alone to facilitate the corresponding recycling scheme; e.g., for applications where arsenic is known not to be present in the water, or where the operation conditions (e.g., pH of the medium) can be adjusted so that the biobased resin alone can be used to adsorb arsenic.

Also, it will be necessary to investigate advanced concepts for designing polyamide thin film composites employed for nanofiltration so that the component materials, polysulfone and polyamide, can be delaminated and recycled at the end of life. Chemical recycling of each of these materials has been being more thoroughly studied than mechanical recycling [90,91], as is the case with other specialty and engineering polymers [92,93]. Recycling these materials is required to save the use of their monomers, some of which are hazardous such as bisphenol A, and to prevent their release into the environment if they are landfilled at the end of life. Alternative, biobased materials with improved functionality for nanofiltration membranes are under investigation (see section S3.2.2).

BMED uses ion exchange membranes. Conventional polymers employed to prepare these membranes include styrene-divinylbenzene, polyethylene, polypropylene and sulfonated polymers [94]. When studying BMED as a possible brine treatment technology, the environmental profile of the constituent materials should be assessed based on similar criteria as those considered to analyse the ion exchange resin for metal removal and nanofiltration membrane materials.

As outlined in section 3.2, the investigation of the combined application of photocatalysis and solar concentration should be extended to analyse the benefits that this would bring in terms of energy and material savings. Regarding this second advantageous aspect, further investigations would enable to find a suitable substrate for the gC_3N_4-photocatalyst that is both resource efficient and stable under solar radiation conditions. Besides, further research would enable to prove that usage of regular (soda lime silicate) glass as the main component of the solar concentration reactor instead of vitreous silica (natural quartz glass) —which is more resource consuming— is possible due to the lack of need to ensure transmittance of ultraviolet radiation for hydrogen peroxide photolysis, since the studied photocatalyst is active under visible radiation.

3.5. Direct emission of greenhouse gases

Another important aspect concerns the estimation of potential direct carbon dioxide emissions emanating from the Waste2Fresh System. The flow of these emissions was estimated by applying a carbon mass balance to the advanced oxidation processes (see section S3.1.1). The results indicate that this flow represents a relatively low contribution (8°%) in the CC category in scenario W2F-Bas0, but a higher contribution in the optimised scenarios (up to 22°% in scenario W2F-Opt3). As an action to inform environmental policies, accounting for direct carbon dioxide emissions from AOPs is highly recommended. This suggestion is in alignment with studies on greenhouse gas emissions from municipal wastewater treatment plants [95,96]. Opportunities for carbon storage or capture are expected to become more accessible to wastewater treatment plants in the next future [96–98].

3.6. Prioritisation of optimisation measures

In the sequence of consecutive optimised scenarios that were built, starting from scenario W2F-Opt1, each group of further optimisation measures was additively aggregated to the group of measures considered in the respective preceding scenario. Consideration of the impact reduction values relative to the maximum reduction values obtained for each impact category (calculated with respect to the scores of scenario W2F-Bas0) shows that it is in scenario W2F-Opt1 where the estimated relative impact reduction values are highest. Subsequent changes in impact reduction are smaller (see Supplementary Table 40). Compared with CS, the impacts of scenario W2F-Opt1 are lower in the FwU and FwE impact categories by factors 5 and 50 respectively, and higher in the other impact categories by factors 3 or lower. In the MMRU impact category, however, the impact of scenario W2F-Opt1 is higher than that of CS by a factor 10. In scenarios W2F-Opt2 and Opt3, the scores in this second group of impact categories approach more closely those of CS: the differences reduce to factors 1 (like in the CC category) or 2, but in the MMRU category the score is still larger than that of CS by a factor 6.

These results support the criterion that the measures defined within scenario W2F-Opt1 should be prioritised. The sequence of possible optimised scenarios was formulated with two main criteria in mind: treatment of brine solutions should be prioritised (measure considered within scenario W2F-Opt1), and the effect of developing more circular supply chains of photovoltaic electricity and some technology materials should be analysed separately. Developing brine treatment schemes towards zero liquid discharge and resource recovery is an important research field, which requires studying pretreatment technologies that are suitable to concentrate brine and remove other components like organic matter [86]. In this study, it is recommended to continue working on characterising the composition of water and brine fractions along the Waste2Fresh System so that, after photocatalysis, the brine mostly contains ionic compounds of known composition (with high purity) that can be concentrated and internally recycled in aqueous form. BMED has been intensively investigated for this purpose and shows specific energy consumption values that, when treating brine with salinity values below certain thresholds (e.g., 1-2 M NaCl), are lower than those of highly energy intensive technologies like evaporation or crystallisation [84,85,99,100]. Although there is a reduced number of previous LCA studies on brine treatment for resource recovery, these indicate that the environmental balance between advanced treatment for resource recovery and savings in the use of primary resources can be positive by using lesser amounts of chemicals (and safer alternative reagents) and energy for the advanced treatment processes [35,36,101]. The present work confirms the results derived from these previous analyses.

3.7. Uncertainties and limitations

During the modelling of the different optimised scenarios, a quantitative assessment of the complete manufacture of LEDs and BMED materials was not included. The information gathered to analyse these two components should be updated and expanded in future work.

The assessment of the effect of potential migration of nanoparticles from the nanocatalysts was only partial due to the lack of data on migration testing. Future studies should be conducted to determine if migration of nanoparticles occurs with the final goal of establishing measures to prevent releases or establishing appropriate exposure limits if migration cannot be completely avoided. Also, additional (eco-)toxicological studies would be needed to characterise the gC_3N_4 material. While the results obtained for the Fe_3O_4-based catalyst highlight the importance of mitigating nanomaterials emissions, they are not valid for a classical risk assessment, which remains essential to ensure that reclaimed water is safe to humans and the environment.

Furthermore, some limitations of this study are associated with the LCA methodology itself. The effect of the temporal variability of some parameters that are known to be highly variable in time should be briefly discussed here. Firstly, the water availability factor of the basin under study was derived from time-averaged data and from a major watershed, which can make the assessment of the water use impact category inaccurate, especially in dry areas, where blue water availability is highly variable in space and time [1], [102]. Additionally, climate change is likely to enhance the frequency of flash floods and flash droughts, which can be predicted but with many uncertainties [2]. Efforts are being undertaken to integrate both dimensions of availability and quality of surface water at the subbasin level [102,103], as well as to evaluate the quality and the extent of groundwater depletion at the subbasin scale [2,104] with the final goal of facilitating the implementation of management actions required to stay within the planetary boundaries for water [1].

Secondly, time-averaged data was used here to estimate the global warming potential of the grid electricity, which may lead to an inaccurate determination of saved amounts of emissions, especially when estimating the energy balance for the scenarios with energy storage. For instance, the average emission factor of the grid comprises renewable energy sources. A more accurate analysis would involve calculating the reduction of greenhouse gas emissions by considering the changes in grid emissions over time, e.g., on an hourly basis [105].

And finally, the dataset used to model the incineration of textile sewage sludge deserves further attention, since it results in the most impactful process in the Conventional System in all the impact categories except in the FwU category (see Supplementary Table 41). To complement the information provided by the applied dataset, which represents the model of a generic hazardous waste incineration process [42], additional data on textile sludge management was analysed (see section S3.3.2). Overall, despite the uncertainty, considering the generic hazardous nature of the sludge may result in estimates of the potential impacts closer to the reality than not considering it.

4. Conclusion

Improving the management of denim wastewater is a global priority, and on-site water recycling represents a promising pathway

toward addressing this challenge. The present LCA analysis examines a pilot-scale case study that reflects the technical and environmental demands of the denim sector. This includes, firstly, the need to treat complex wastewater streams characteristic of contemporary denim production processes, and secondly, the requirement to evaluate where the integrated treatment technologies can surpass existing wastewater treatment practices from both technical and environmental perspectives.

The results indicate that, to optimise the environmental performance of an industrial scale water recycling system, the highest priority should be given to recycling the main constituents of brine and aqueous solutions generated throughout the technology life cycle. Also, the water recycling plant should only use solar energy, and this would require integration of the PV system with an energy storage unit. The technologies applied for brine treatment and for energy supply should be developed with a strong emphasis on the recyclability of their constituent materials.

When studying the implementation of these measures, action to reduce energy use at the design and operation stages of the most energy-consumptive processes should be considered. In addition to this, measurements should be conducted to determine if migration of nanoparticles from the catalyst materials occurs with the final goal of designing measures for preventing or minimising this process, and wastewater should be analysed in more detail regarding its content of salts and dissolved organic matter.

Funding sources

This work received funding from the European Union Horizon 2020 research and innovation funding programme under grant agreement No. 958491.

CRediT authorship contribution statement

Mercè Font-Brucart: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Christoph Studer:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft. **Cristian Blanco-Tirado:** Resources, Writing – review & editing. **Marianny Y. Combariza:** Resources. **Michele Orlandi:** Resources, Writing – review & editing. **Pinar Karagoz:** Resources, Writing – review & editing. **Irwing Ramirez:** Resources. **Ajay Kumar:** Resources. **Satheesh Krishnamurthy:** Resources, Writing – review & editing. **Jesús Cordón:** Resources, Writing – review & editing. **Claudio Fernández-Acevedo:** Resources. **Samson Akanbi:** Resources, Writing – review & editing. **Erdem Kestioglu:** Resources, Writing – review & editing. **Tobias Walser:** Conceptualization, Funding acquisition, Writing – review & editing. **Roland Hischier:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

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

Acknowledgements

We are grateful to the data provided by Serpil Cetin Edebali and her team at KTUN, Richard Burke (Nanofique Limited), and Phill Jones and his team at CPI. We are grateful to all the interesting discussions held during the project with Linmei Nie (CSDI) on the rainwater harvesting system, with Viktoriya Pyeshkova (IMBG) on the biological sensors, with Marco Bettonte (UNITN) on solar concentrators, with Yvonne L. Kohl (Fraunhofer) on the safety of nanomaterials, with Foteini Petrakli and Michalis Galatoulas (IRES) on the life cycle cost assessment, and with Mykolas S. Poskus (SICE) on the social acceptance of sustainable wastewater treatment technologies. Overall, we are grateful to all the partners of the Waste2Fresh project for the good collaboration.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wri.2026.100375.

Data availability

The datasets on the technologies are confidential. A summary of the data used to study the technologies and the additional data collected are available in the supplementary material.

References

[1] Global Commission on the Economics of Water-GCEW, The economics of water: valuing the hydrological cycle as a global common goal. https://economicsofwater.watercommission.org/, 2024.
[2] Joint Research Centre-JRC and United Nations Convention to Combat Desertification-UNCCD, World Drought Atlas, Publications Office, Luxembourg, 2024. https://data.europa.eu/doi/10.2760/3842670.

[3] D. Francis, Global maps of purified recycled water for drinking, Water Serv. Assoc. Austr. (2024). https://water360.com.au/wp-content/uploads/2024/12/WSAA-PRW-maps-241202.pdf.
[4] United Nations-UN Water, Integrated Monitoring Initiative for SDG 6, 2024. https://www.unwater.org/our-work/integrated-monitoring-initiative-sdg-6.
[5] World Health Organisation-WHO, Water Safety Plan Manual: Step-By-Step Risk Management for drinking-water Suppliers, second ed., 2023. Geneva.
[6] European Parliament-EP and Council of the European Union-CEU, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy, 2000.
[7] EP and CEU, Directive 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption, 2020.
[8] EP and CEU, Directive 2024/3019 of the European Parliament and of the Council of 27 November 2024 Concerning Urban Wastewater Treatment, 2024.
[9] EP and CEU, Regulation 2020/741 of the European Parliament and of the Council of 25 May 2020 on Minimum Requirements for Water Reuse, 2020.
[10] United Nations Environment Programme-UNEP, Corporate sustainability reporting. https://www.unep.org/explore-topics/resource-efficiency/what-we-do/responsible-industry/corporate-sustainability, 2026.
[11] EP and CEU, Directive 2022/2464 of the European Parliament and of the Council of 14 December 2022 Amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as Regards Corporate Sustainability Reporting, 2022.
[12] EP and CEU, Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial and Livestock Rearing Emissions (Integrated Pollution Prevention and Control), 2010.
[13] European Commission-EC, EU Strategy for Sustainable and Circular Textiles, 2022.
[14] A.P. Periyasamy, S. Periyasami, Critical review on sustainability in denim: a step toward sustainable production and consumption of denim, ACS Omega 8 (5) (2023) 4472–4490, https://doi.org/10.1021/acsomega.2c06374.
[15] S. Roos, C. Jönsson, S. Posner, R. Arvidsson, M. Svanström, An inventory framework for inclusion of textile chemicals in life cycle assessment, Int. J. Life Cycle Assess. 24 (5) (2019) 838–847, https://doi.org/10.1007/s11367-018-1537-6.
[16] ZDHC Foundation, ZDHC wastewater guidelines. https://downloads.roadmaptozero.com/output/ZDHC-Wastewater-Guidelines, 2022.
[17] J. Roth, B. Zerger, D. De Geeter, J. Gómez Benavides, S. Roudier, Best Available Techniques (BAT) Reference Document for the Textiles Industry: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), Joint Research Centre, 2023.
[18] V. Buscio, C. Gutiérrez-Bouzán, Chemicals and effluent treatment in indigo denim processes, in: S.S. Muthu (Ed.), Sustainability in Denim, Woodhead Publishing, 2017, pp. 235–255.
[19] Archroma, Indigo flow: the archroma way: an aniline-free indigo system that produces authentic denim without compromising our planet. https://marketplace.chemsec.org/, 2023.
[20] M. Vedrenne, R. Vasquez-Medrano, D. Prato-Garcia, B.A. Frontana-Uribe, M. Hernandez-Esparza, J.M. de Andrés, A ferrous oxalate mediated photo-Fenton system: toward an increased biodegradability of indigo dyed wastewaters, J. Hazard Mater. 243 (2012) 292–301, https://doi.org/10.1016/j.jhazmat.2012.10.032.
[21] M. Sanchez, in: R. Paul Denim (Ed.), Dyeing of Denim Yarns with Non-indigo Dyes, Elsevier, 2015, pp. 107–157, https://doi.org/10.1016/B978-0-85709-843-6.00005-6.
[22] R.B. Chavan, in: R. Paul Denim (Ed.), Indigo Dye and Reduction Techniques, Elsevier, 2015, pp. 37–67, https://doi.org/10.1016/B978-0-85709-843-6.00003-2.
[23] G.N. Bidart, et al., Chemoenzymatic indican for light-driven denim dyeing, Nat. Commun. 15 (1) (2024) 1489, https://doi.org/10.1038/s41467-024-45749-3.
[24] M. Božič, V. Kokol, Ecological alternatives to the reduction and oxidation processes in dyeing with vat and sulphur dyes, Dyes Pigments 76 (2) (2008) 299–309, https://doi.org/10.1016/j.dyepig.2006.05.041.
[25] Chavan, Environmentally friendly dyes, in: M. Clark (Ed.), Handbook of Textile and Industrial Dyeing : Principles, Processes and Types of Dyes, first ed., Woodhead Publishing, 2011.
[26] M. Cordin, T. Bechtold, T. Pham, Quantification of aniline and N-methylaniline in indigo, Sci. Rep. 11 (1) (2021) 21135, https://doi.org/10.1038/s41598-021-00634-7.
[27] A.P. Periyasamy, Evaluation of microfiber release from jeans: the impact of different washing conditions, Environ. Sci. Pollut. Res. 28 (41) (2021) 58570–58582, https://doi.org/10.1007/s11356-021-14761-1.
[28] P. Westerhoff, et al., Low risk posed by engineered and incidental nanoparticles in drinking water, Nat. Nanotechnol. 13 (8) (2018) 661–669, https://doi.org/10.1038/s41565-018-0217-9.
[29] S. Rajkovic, N.A. Bornhöft, R. van der Weijden, B. Nowack, V. Adam, Dynamic probabilistic material flow analysis of engineered nanomaterials in European waste treatment systems, Waste Manag. 113 (2020) 118–131, https://doi.org/10.1016/j.wasman.2020.05.032.
[30] J.R. Peller, L. Eberhardt, R. Clark, C. Nelson, E. Kostelnik, C. Iceman, Tracking the distribution of microfiber pollution in a southern Lake Michigan watershed through the analysis of water, sediment and air, Environ. Sci. Process. Impacts 21 (9) (2019) 1549–1559, https://doi.org/10.1039/C9EM00193J.
[31] J.E. Drewes, N. Horstmeyer, Recent developments in potable water reuse, in: D. Fatta-Kassinos, D.D. Dionysiou, K. Kümmerer (Eds.), Advanced Treatment Technologies for Urban Wastewater Reuse vol. 45, Springer International Publishing, Cham, 2015, pp. 269–290, https://doi.org/10.1007/698_2015_341. The Handbook of Environmental Chemistry, vol. 45.
[32] International Organization for Standardization-ISO, International Standard: ISO 14044: Environmental Management: Life Cycle Assessment: Requirements and Guidelines, 2006.
[33] P. Fantke, et al., Advancements in life cycle human exposure and toxicity characterization, Environ. Health Perspect. 126 (12) (2018) 125001, https://doi.org/10.1289/EHP3871.
[34] I. Garmendia Aguirre, et al., Safe and Sustainable by Design Chemicals and Materials. Revised Framework (2025), 2025, https://doi.org/10.2760/5103785.
[35] M.-D. Álvarez, V. Buscio, V. López-Grimau, C. Gutiérrez-Bouzán, LCA study of a new electrochemical and ultraviolet (EC-UV) combined system to decolourise and reuse textile saline effluents: environmental evaluation and proposal to improve the production process, Chem. Eng. J. 392 (2020) 123696, https://doi.org/10.1016/j.cej.2019.123696.
[36] S. Harris, G. Tsalidis, J.B. Corbera, J.J. Espi Gallart, F. Tegstedt, Application of LCA and LCC in the early stages of wastewater treatment design: a multiple case study of brine effluents, J. Clean. Prod. 307 (2021) 127298, https://doi.org/10.1016/j.jclepro.2021.127298.
[37] S. Mohan, N. Oke, D. Gokul, Conventional and zero liquid discharge treatment plants for textile wastewater through the lens of carbon footprint analysis, J. Water Clim. Change 12 (5) (2021) 1392–1403, https://doi.org/10.2166/wcc.2020.100.
[38] M.S. Poškus, L. Jovarauskaitė, A. Balundė, A systematic review of drivers of sustainable wastewater treatment technology adoption, Sustainability 13 (15) (2021), https://doi.org/10.3390/su13158584.
[39] A. El Golli, et al., Parabolic trough concentrator design, characterization, and application: solar wastewater purification targeting textile industry dyes and pharmaceuticals—Techno-economic study, Euro-Mediterr J Environ Integr 9 (4) (2024) 1907–1919, https://doi.org/10.1007/s41207-024-00531-1.
[40] V. Pyeshkova, O. Soldatkin, T. Velychko, V. Arkhypova, S. Dzyaderych, A. Soldatkin, Conductometric biosensor based on butyrylcholinesterase for determination of toxic substances in water samples, in: IEEE 11th International Conference on 'Nanomaterials: Applications & Properties' (NAP-2021), 2021.
[41] O.O. Soldatkin, et al., Application of butyrylcholinesterase-based biosensor for simultaneous determination of different toxicants using inhibition and reactivation steps, Electroanalysis 36 (6) (2024) e202300400, https://doi.org/10.1002/elan.202300400.
[42] ecoinvent Association, Ecoinvent. https://ecoinvent.org/, 2025.
[43] EC, Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations, 2021.
[44] Pre Sustainability, SimaPro, 2025. https://pre-sustainability.com/.
[45] P. Fantke, et al., USEtox® 2.0: Documentation, USEtox International Center, 2018.

[46] A.Y. Hoekstra, A.K. Chapagain, M.M. Aldaya, M.M. Mekonnen, The Water Footprint Assessment Manual: Setting the Global Standard, Earthscan from Routledge, London Washington, D.C, 2011, https://doi.org/10.4324/9781849775526.
[47] R. Paul, R.S. Blackburn, T. Bechtold, Indigo and indigo colorants, in: Ullmann's Encyclopedia of Industrial Chemistry, first ed., Wiley-VCH Verlag GmbH & Co. KGaA, Ed., Wiley, 2021, pp. 1–16, https://doi.org/10.1002/14356007.a14_149.pub3.
[48] Organisation for Economic Cooperation and Development-OECD and UNEP, Indigo blue 3H-Indol-3-one, 2-(1,3-dihydro-3-oxo-2H-indol-2-ylidene)-1,2-dihydro CAS N°: 482-89-3. https://hpvchemicals.oecd.org, 2012.
[49] European Chemicals Agency-ECHA, ECHA CHEM: ECHA chemicals database. https://chem.echa.europa.eu/, 2025.
[50] W.H. Clements, C. Kotalik, Effects of major ions on natural benthic communities: an experimental assessment of the US environmental protection agency aquatic life benchmark for conductivity, Freshw. Sci. 35 (1) (2016) 126–138, https://doi.org/10.1086/685085.
[51] E. Estévez, T. Rodríguez-Castillo, A.M. González-Ferreras, M. Cañedo-Argüelles, J. Barquín, Drivers of spatio-temporal patterns of salinity in Spanish rivers: a nationwide assessment, Philos. Trans. R. Soc. B 374 (1764) (2019) 20180022, https://doi.org/10.1098/rstb.2018.0022.
[52] L.A. Golding, et al., The influence of salinity on the chronic toxicity of shale gas flowback wastewater to freshwater organisms, J. Hazard Mater. 428 (2022) 128219, https://doi.org/10.1016/j.jhazmat.2022.128219.
[53] A.R. Lopez, D.R. Hesterberg, D.H. Funk, D.B. Buchwalter, Bioaccumulation dynamics of arsenate at the base of aquatic food webs, Environ. Sci. Technol. 50 (12) (2016) 6556–6564, https://doi.org/10.1021/acs.est.6b01453.
[54] C.A. Mebane, R.J. Eakins, B.G. Fraser, W.J. Adams, Recovery of a mining-damaged stream ecosystem, Elem. Sci. Anth. 3 (2015) 000042, https://doi.org/10.12952/journal.elementa.000042.
[55] L. Posthuma, J. Van Gils, M.C. Zijp, D. Van De Meent, D. De Zwart, Species sensitivity distributions for use in environmental protection, assessment, and management of aquatic ecosystems for 12 386 chemicals, Environ. Toxicol. Chem. 38 (4) (2019) 905–917, https://doi.org/10.1002/etc.4373.
[56] B.H. Gursoy-Haksevenler, E. Atasoy-Aytis, M. Dilaver, Y. Karaaslan, Treatability of hazardous substances in industrial wastewater: case studies for textile manufacturing and leather production sectors, Environ. Monit. Assess. 194 (5) (2022) 383, https://doi.org/10.1007/s10661-022-09982-x.
[57] WHO, Potable Reuse: Guidance for Producing Safe drinking-water. Geneva, 2017. https://iris.who.int/handle/10665/258715. (Accessed 21 March 2025).
[58] P.T. Anastas, Handbook of Green Chemistry, first ed., Wiley, 2010 https://doi.org/10.1002/9783527628698.
[59] J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: an analysis of 114 definitions, Resour. Conserv. Recycl. 127 (2017) 221–232, https://doi.org/10.1016/j.resconrec.2017.09.005.
[60] W. Lawler, J. Alvarez-Gaitan, G. Leslie, P. Le-Clech, Comparative life cycle assessment of end-of-life options for reverse osmosis membranes, Desalination 357 (2015) 45–54, https://doi.org/10.1016/j.desal.2014.10.013.
[61] L. Svoboda, et al., Graphitic carbon nitride nanosheets as highly efficient photocatalysts for phenol degradation under high-power visible LED irradiation, Mater. Res. Bull. 100 (2018) 322–332, https://doi.org/10.1016/j.materresbull.2017.12.049.
[62] F. Dong, L. Wu, Y. Sun, M. Fu, Z. Wu, S.C. Lee, Efficient synthesis of polymeric g-C3N4 layered materials as novel efficient visible light driven photocatalysts, J. Mater. Chem. 21 (39) (2011) 15171, https://doi.org/10.1039/c1jm12844b.
[63] C. Lv, et al., Selective electrocatalytic synthesis of urea with nitrate and carbon dioxide, Nat. Sustain. 4 (10) (2021) 868–876, https://doi.org/10.1038/s41893-021-00741-3.
[64] T. Pilevneli, G. Capar, C. Sánchez-Cerdà, Investigation of climate change impacts on agricultural production in Turkey using volumetric water footprint approach, Sustain. Prod. Consum. 35 (2023) 605–623, https://doi.org/10.1016/j.spc.2022.12.013.
[65] A.H.D.S. Filho, et al., Photoinduced degradation of indigo carmine: insights from a computational investigation, J. Mol. Model. 26 (11) (2020) 309, https://doi.org/10.1007/s00894-020-04567-2.
[66] M.M. Sousa, et al., A photochemical study on the blue dye indigo: from solution to ancient Andean textiles, Photochem. Photobiol. Sci. 7 (11) (2008) 1353–1359, https://doi.org/10.1039/b809578g.
[67] M. Owsianiak, et al., Ecotoxicity characterization of chemicals: global recommendations and implementation in USEtox, Chemosphere 310 (2023) 136807, https://doi.org/10.1016/j.chemosphere.2022.136807.
[68] L.M.M. Kinsman, B.T. Ngwenya, C.A. Morrison, J.B. Love, Tuneable separation of gold by selective precipitation using a simple and recyclable diamide, Nat. Commun. 12 (1) (2021) 6258, https://doi.org/10.1038/s41467-021-26563-7.
[69] E.S. Breuninger, et al., Marine and terrestrial contributions to atmospheric deposition fluxes of methylated arsenic species, Nat. Commun. 15 (1) (2024) 9623, https://doi.org/10.1038/s41467-024-53974-z.
[70] A. Kumar, A. Thorbole, R.K. Gupta, Sustaining the future: semiconductor materials and their recovery, Mater. Sci. Semicond. Process. 185 (2025) 108943, https://doi.org/10.1016/j.mssp.2024.108943.
[71] I.M. Peters, C.J. Brabec, The ideal recyclable solar cell, Nat. Rev. Chem 9 (7) (2025) 427–429, https://doi.org/10.1038/s41570-025-00728-0.
[72] D. Ziegenbalg, Selected aspects of photoreactor engineering, in: J. Strunk (Ed.), Heterogeneous Photocatalysis, first ed., Wiley, 2021, pp. 155–186, https://doi.org/10.1002/9783527815296.ch7.
[73] S. Dominguez, et al., LCA of greywater management within a water circular economy restorative thinking framework, Sci. Total Environ. 621 (2018) 1047–1056, https://doi.org/10.1016/j.scitotenv.2017.10.122.
[74] H.H. De Simone Souza, et al., Environmental assessment of a single-family photocatalytic greywater treatment system based on the design and operating conditions, Sustain. Prod. Consum. 35 (2023) 483–494, https://doi.org/10.1016/j.spc.2022.12.001.
[75] N. Aquino De Carvalho, L.M. Gilbertson, Comparative life cycle assessment of graphitic carbon nitride synthesis routes, J. Ind. Ecol. 27 (3) (2023) 1008–1020, https://doi.org/10.1111/jiec.13390.
[76] G. Matafonova, V. Batoev, Recent advances in application of UV light-emitting diodes for degrading organic pollutants in water through advanced oxidation processes: a review, Water Res. 132 (2018) 177–189, https://doi.org/10.1016/j.watres.2017.12.079.
[77] H. Pedersen, S.T. Barry, J. Sundqvist, Green CVD—Toward a sustainable philosophy for thin film deposition by chemical vapor deposition, J. Vac. Sci. Technol. A 39 (5) (2021) 051001, https://doi.org/10.1116/6.0001125.
[78] W. Gao, et al., Criticality assessment of metal resources for light-emitting diode (LED) production – a case study in China, Clean. Eng. Technol. 6 (2022) 100380, https://doi.org/10.1016/j.clet.2021.100380.
[79] A. Gassmann, J. Zimmermann, R. Gauss, R. Stauber, O. Gutfleisch, LED lamps recycling technology for a circular economy, in: LED Professional vol. 56, Luger Research, 2016.
[80] R.P. De Oliveira, J. Benvenuti, D.C.R. Espinosa, A review of the current progress in recycling technologies for gallium and rare earth elements from light-emitting diodes, Renew. Sustain. Energy Rev. 145 (2021) 111090, https://doi.org/10.1016/j.rser.2021.111090.
[81] M.A. Reuter, A. Van Schaik, Product-centric simulation-based design for recycling: case of LED lamp recycling, J. Sustain. Metall. 1 (1) (2015) 4–28, https://doi.org/10.1007/s40831-014-0006-0.
[82] F. Rahman, From Edison to LEDs: the Science and Story of Light Sources, World Scientific, 2023, https://doi.org/10.1142/13178.
[83] Y.W. Berkessa, et al., Anion exchange membrane organic fouling and mitigation in salt valorization process from high salinity textile wastewater by bipolar membrane electrodialysis, Desalination 465 (2019) 94–103, https://doi.org/10.1016/j.desal.2019.04.027.
[84] A. Culcasi, et al., Towards sustainable production of minerals and chemicals through seawater brine treatment using Eutectic freeze crystallization and electrodialysis with bipolar membranes, J. Clean. Prod. 368 (2022) 133143, https://doi.org/10.1016/j.jclepro.2022.133143.
[85] J. Lin, et al., Toward resource recovery from textile wastewater: dye extraction, water and base/acid regeneration using a hybrid NF-BMED process, ACS Sustainable Chem. Eng. 3 (9) (2015) 1993–2001, https://doi.org/10.1021/acssuschemeng.5b00234.
[86] G.U. Semblante, J.Z. Lee, L.Y. Lee, S.L. Ong, H.Y. Ng, Brine pre-treatment technologies for zero liquid discharge systems, Desalination 441 (2018) 96–111, https://doi.org/10.1016/j.desal.2018.04.006.

[87] A. Gallego-Schmid, R.R.Z. Tarpani, S. Miralles-Cuevas, A. Cabrera-Reina, S. Malato, A. Azapagic, Environmental assessment of solar photo-Fenton processes in combination with nanofiltration for the removal of micro-contaminants from real wastewaters, Sci. Total Environ. 650 (2019) 2210–2220, https://doi.org/10.1016/j.scitotenv.2018.09.361.
[88] I. Muñoz, J. Peral, J. Antonio Ayllón, S. Malato, P. Passarinho, X. Domènech, Life cycle assessment of a coupled solar photocatalytic–biological process for wastewater treatment, Water Res. 40 (19) (2006) 3533–3540, https://doi.org/10.1016/j.watres.2006.08.001.
[89] B. Wilhelmus, et al., Chemical recycling, in: N. Niessner (Ed.), Recycling of Plastics, Hanser, 2022, pp. 435–594, https://doi.org/10.3139/9781569908570.009.
[90] Y. Liu, et al., In situ enhancive and closed-loop chemical recyclable high-performance aromatic polyamides from lignin-derived ferulic acid, ACS Sustainable Chem. Eng. 13 (2) (2025) 1106–1117, https://doi.org/10.1021/acssuschemeng.4c09354.
[91] L. Wang, et al., Aminolytic depolymerization of polyarylsulfones, Polym. Degrad. Stabil. 103 (2014) 69–74, https://doi.org/10.1016/j.polymdegradstab.2014.03.013.
[92] H. Mitta, et al., Challenges and opportunities in catalytic hydrogenolysis of oxygenated plastics waste: polyesters, polycarbonates, and epoxy resins, Green Chem. 27 (1) (2025) 10–40, https://doi.org/10.1039/d4gc03784g.
[93] A. Sekar, et al., Sustainable fire-safe epoxy composites enabled by reactive polyphosphonates, Chem. Eng. J. 520 (2025) 165779, https://doi.org/10.1016/j.cej.2025.165779.
[94] A. Campione, L. Gurreri, M. Ciofalo, G. Micale, A. Tamburini, A. Cipollina, Electrodialysis for water desalination: a critical assessment of recent developments on process fundamentals, models and applications, Desalination 434 (2018) 121–160, https://doi.org/10.1016/j.desal.2017.12.044.
[95] Y. Law, G.E. Jacobsen, A.M. Smith, Z. Yuan, P. Lant, Fossil organic carbon in wastewater and its fate in treatment plants, Water Res. 47 (14) (2013) 5270–5281, https://doi.org/10.1016/j.watres.2013.06.002.
[96] C. Song, J.-J. Zhu, Z. Yuan, M.C.M. Van Loosdrecht, Z.J. Ren, Defining and achieving net-zero emissions in the wastewater sector, Nat. Water 2 (10) (2024) 927–935, https://doi.org/10.1038/s44221-024-00318-2.
[97] EP and CEU, Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 Establishing a Union Certification Framework for Permanent Carbon Removals, Carbon Farming and Carbon Storage in Products, 2024.
[98] N. Jardin, Towards a Sustainable Future: Ruhrverband's Path to Energy Neutrality and Climate Resilience, International Water Association - IWA, 2025. https://iwa-network.org/towards-a-sustainable-future-ruhrverbands-path-to-energy-neutrality-and-climate-resilience/.
[99] D. Ankoliya, et al., Techno-economic analysis of integrated bipolar membrane electrodialysis and batch reverse osmosis for water and chemical recovery from dairy wastewater, J. Clean. Prod. 420 (2023) 138264, https://doi.org/10.1016/j.jclepro.2023.138264.
[100] G. Cipolletta, N. Lancioni, Ç. Akyol, A.L. Eusebi, F. Fatone, Brine treatment technologies towards minimum/zero liquid discharge and resource recovery: state of the art and techno-economic assessment, J. Environ. Manag. 300 (2021) 113681, https://doi.org/10.1016/j.jenvman.2021.113681.
[101] N. Elginoz, C. Papadaskalopoulou, S. Harris, Using life cycle assessment at an early stage of design and development of zero discharge brine treatment and recovery, Water Resour. Ind. 28 (2022) 100184, https://doi.org/10.1016/j.wri.2022.100184.
[102] L. Scherer, A. Venkatesh, R. Karuppiah, S. Pfister, Large-scale hydrological modeling for calculating water stress indices: implications of improved spatiotemporal resolution, surface-groundwater differentiation, and uncertainty characterization, Environ. Sci. Technol. 49 (8) (2015) 4971–4979, https://doi.org/10.1021/acs.est.5b00429.
[103] M. Wang, et al., A triple increase in global river basins with water scarcity due to future pollution, Nat. Commun. 15 (1) (2024) 880, https://doi.org/10.1038/s41467-024-44947-3.
[104] I.E.M. De Graaf, T. Gleeson, L.P.H. (Rens) Van Beek, E.H. Sutanudjaja, M.F.P. Bierkens, Environmental flow limits to global groundwater pumping, Nature 574 (7776) (2019) 90–94, https://doi.org/10.1038/s41586-019-1594-4.
[105] D. Beloin-Saint-Pierre, P. Padey, B. Périsset, V. Medici, Considering the dynamics of electricity demand and production for the environmental benchmark of Swiss residential buildings that exclusively use electricity, IOP Conf. Ser. Earth Environ. Sci. 323 (1) (2019) 012096, https://doi.org/10.1088/1755-1315/323/1/012096.