

Deliverable Report D3.2 LCA and LCC results

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1 Introduction to the project SERPIC

The project *Sustainable Electrochemical Reduction of contaminants of emerging concern and Pathogens in WWTP effluent for Irrigation of Crops – SERPIC* will develop an integral technology, based on a multi-barrier approach, to treat the effluents of wastewater treatment plants (WWTPs) to maximise the reduction of contaminants of emerging concern (CECs). The eight partners of the SERPIC consortium are funded by the European Commission and by six national funding agencies from Norway, Germany, Italy, Spain, Portugal and South Africa. The official starting date of the SERPIC project is 1st September 2021. The project has a duration of 40 months and will end on 31st December 2024.

The overall aim of the SERPIC project is to investigate and minimise the spread of CECs and antimicrobial resistant bacteria/antibiotic resistance genes (ARB/ARG) within the water cycle from households and industries to WWTPs effluents, and afterwards via irrigation into the food chain, into soil and groundwater and into river basins, estuaries, coastal areas, and oceans with a focus on additional water sources for food production.

A membrane nanofiltration (NF) technology will be applied to reduce CECs in its permeate stream by at least 90 % while retaining the nutrients. A residual disinfection using chlorine dioxide produced electrochemically will be added to the stream used for crops irrigation (Route A). The CECs in the polluted concentrate (retentate) stream will be reduced by at least 80 % by light driven electro-chemical oxidation. When discharged into the aquatic system (route B), it will contribute to the quality improvement of the surface water body.

A prototype treatment plant will be set-up and evaluated for irrigation in long-term tests with the help of agricultural test pots. A review investigation of CECs spread will be performed at four regional showcases in Europe and Africa. It will include a detailed assessment of the individual situation and surrounding condition. Transfer concepts will be developed to transfer the results of the treatment technology to other regions, especially in low- and middle-income countries.

2 Report summary

Two standardised analyses have been carried out to evaluate the cost and environmental status of the SERPIC system: Life Cycle Costing (LCC) is used to examine the cost of manufacturing and operating SERPIC systems, while Life Cycle Assessment (LCA) is used to analyse material and energy consumption, as well as the influence in the impact categories associated with the construction of the SERPIC prototype. These impact categories include carbon footprint, water footprint, human toxicity and impact on ecosystems. In addition to these assessments, a plan to manage the risk (the Sanitation Safety Plan SSP) in the case of reuse of reclaimed water must be developed, according to the EU regulation on reclaimed water reuse. The first step in this direction implies the evaluation of the main risks associated to the treatment. To pursue this aim, a Failure Mode, Effects, and Criticality Analysis (FMECA) was carried out and the effects of the failure modes of the different SERPIC treatment components were identified with regard the quality of the final effluent and its adequateness for irrigation needs. The analysis identified the main risks associated to the failure modes which may happen and which preventive measures should be to adopt to reduce them.

3 Deliverable description as stated in the Project Description

A report including the most relevant aspects of the LCA and LCC carried out in **T3.2** about the SERPIC solution (based on our own data obtained in the project) and compared with actual treatments currently applied (based on existing literature data) will be made.

4 Methods and Data

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) have been used to evaluate the impacts generated by the technologies of the SERPIC Project applied for reuse of the effluents of WWTPs. The reported LCA and LCC study was carried out in accordance with the ISO 14040 and ISO 14044 international standards (ISO, 2006a; ISO, 2006b). SimaPro 9.3.0.3 and Ecoinvent 3.3 database were used as software tool and database, respectively. SimaPro is the most frequently used life assessment tool for evaluating the environmental impact of processes or technologies from industrial and academic perspectives. The software provides sustainability insights that can further enhance the production of a product and improve the delivery of a service. ReCiPe, AWARE, USEtox Midpoint methods were used to point out a large variety of impacts associated with the SERPIC technology. Midpoint indicators are intermediate measures of environmental impact that reflect the changes in the natural environment caused by emissions or resource use. These Midpoint methodologies were used to quantify the environmental burden into four impact categories comprising the carbon footprint or global warming potential (GWP) (Fernández-Marchante et al., 2020), the water footprint (Boulay et al., 2018), the human toxicity (non-cancer) (Fernández-Marchante et al., 2021) and the Freshwater ecotoxicity (Fernández-Marchante et al., 2024).

Therefore, the environmental impact of the SERPIC process was quantified according to these impact categories for the different energy and life span scenarios proposed. The following impact categories were selected as the most interesting for this project. The functional unit (FU) was assumed to be 1 litre of treated effluents of WWTPs, so all the environmental impact are standardized based on this magnitude. Although the plant was previously divided into three sub-sections: two related to the production of the oxidants (ozone and persulphate), and a third related to the treatment, incorporating the nanofiltration unit and the photoreactor. The inventories for water treatment and oxidant production are shown in **Table 1**, **Table 2** and **Table 3**, respectively.

Table 1. Life cycle inventory for the SERPIC water treatment process.

Equipment	Material	Units	Weight (g/u)	Optimistic life span (h)	Moderate life span (h)	Conservative life span (h)				
Feeding pump	Polyethylene		1120							
	Stainless steel	2	650	10000	5000	1250				
	Wiring		20.6							
	Electronic material		59.4							
PVC	1		175				10000	5000	1250	
Recirculation pump	Stainless steel		75							
	PVC	1	175	10000	5000	1250				
Photoreactor feeding pump	Stainless steel	1	75	10000	5000	1250				
	Membrane (ABS)		200	10000	5000	1250				
Nanofiltration	Electronic components		170							
	Stainless steel	1	10	20000	10000	2500				
	Housing		75							
	Filters (PVC)		545							
	Tubing (Ozone feed)		Silicone				1	51.8	10000	5000
Tubing (Persulfate feed)	Silicone		1				51.8	5000	2500	625
Water disinfection tank	PVC	1	2570	20000	20000	20000				
Tank cover	PVC	1	1156	20000	20000	20000				
Support tank (photoreactor)	PVC	1	2570	20000	20000	20000				
Tank cover	PVC	1	1156	20000	20000	20000				
Photoreactor	Teflon	1	200	2500	10000	20000				
	UV lamp	4	235	937	3750	7500				
	Wiring UV lamp	4	125	937	3750	7500				
	Aluminium	1	300	2500	10000	20000				
	Aluminium Oxide	1	300	2500	10000	20000				
	Borosilicate	1	3300	2500	10000	20000				
	Electronic material	1	500	2500	10000	20000				
	Stainless steel	1	11400	2500	10000	20000				
	Wiring	1	500	2500	10000	20000				
T-joint	Nylon 6-6	1	10	10000	5000	1250				
Straight pipes	Nylon 6-6	1	10.2	10000	5000	1250				
Elbow joints (blue)	Nylon 6-6	2	10.6	10000	5000	1250				
Elbow joints (grey)	Nylon 6-6	1	10.8	10000	5000	1250				
Valves (Ozone line)	Nylon 6-6	1	41.8	10000	5000	1250				
Valves (persulfate line)	Nylon 6-6	2	1	5000	2500	625				
T-joint (ozone line)	Nylon 6-6	1	10	5000	2500	625				
Straight pipes (ozone line)	Nylon 6-6	1	10.2	5000	2500	625				
Elbow joints (blue, ozone line)	Nylon 6-6	8	10.6	5000	2500	625				
Elbow joints (grey, ozone line)	Nylon 6-6	2	10.8	5000	2500	625				
Transformer	Electronic components		8							
	Polyethylene	1	48	20000	10000	2500				
	Stainless steel		16							
	Wiring		8							

Table 2. Life cycle inventory for the electrochemical production of persulfate.

Equipment	Material	Units	Weight (g/u)	Optimistic life Span (h)	Moderate life span (h)	Conservative life span (h)
Pump	Stainless steel	3	59.61	10000	5000	1250
	Polyethylene		22.4			
Tecalán pipe (6 mm)	Tetrafluoroethylene (50%)	1	10.5	10000	5000	1250
	Polyurethane (50%)		10.5			
Tecalán pipe (10 mm)	Tetrafluoroethylene (50%)	1	14.9	10000	5000	1250
	Polyurethane (50%)		14.9			
Blue joint	Nylon 6-6	1	10.6	10000	5000	1250
Grey joints	Nylon 6-6	8	10.8	10000	5000	1250
Valves	Nylon 6-6	2	41.8	10000	5000	1250
Straight pipe	Nylon 6-6	1	10.2	10000	5000	1250
Shell	Polyethylene (70%)	1	765.9	10000	5000	1250
	Polypropylene (30%)		255.3			
Flow distributor	Polyethylene (75%)	1	11.85	10000	5000	1250
	Polypropylene (25%)		35.55			
Steel screws	Stainless steel	10	17.6	20000	20000	2000
Electrochemical cell	Transparent film	2	12.6	10000	5000	1250
	Black film	2	23	10000	5000	1250
Anode	BDD	1	182.6	10000	5000	1250
Cathode	Stainless steel	1	139.6	10000	5000	1250
Temperature distributor	Stainless steel	1	86.6	10000	5000	1250
Feeding tank (H ₂ SO ₄)	PVC	1	1200	20000	20000	20000
Recirculation tank	PVC	1	2036	20000	20000	20000
	PVC		1156			
Air cooler	PVC	1	70	20000	10000	2500
	Stainless steel		10			
Refrigeration tank	PVC	1	1700	20000	20000	20000

Table 3. Life cycle inventory for ozone production

Equipment	Material	Units	Weight (g/u)	Optimistic life Span (h)	Moderate life span (h)	Conservative life span (h)																																																																																																																
Pump	Stainless steel	2	59.61	10000	5000	1250																																																																																																																
	Polyethylene		22.4				Tecalán pipe (6 mm)	Tetrafluoroethylene (50%)	1	10.5	10000	5000	1250	Polyurethane (50%)	10.5	Tecalán pipe (10 mm)	Tetrafluoroethylene (50%)	1	14.9	10000	5000	1250	Polyurethane (50%)	14.9	Blue joint	Nylon 6-6	1	10.6	10000	5000	1250	Grey joints	Nylon 6-6	8	10.8	10000	5000	1250	Valves	Nylon 6-6	2	41.8	10000	5000	1250	Straight pipe	Nylon 6-6	1	10.2	10000	5000	1250	Shell	Methacrylate (60%)	1	192.5	10000	5000	1250	Polyurethane (40%)	128.3	Steel screws	Stainless steel	12	38.2	10000	5000	1250	Titanium screws	Titanium	2	13.6	10000	5000	1250	Electrochemical cell	Electrodes	2	30.75	10000	5000	1250	Nafion membrane	Polytetrafluoroethylene	1	3.04	10000	5000	1250	Sulphuric acid	2.2	Joists	Silicone	2	16.9	10000	5000	1250	Recirculation tank	PVC	1	2036	20000	20000	20000	PVC	1156	Air cooler	PVC	1	70	20000	10000	2500	Stainless steel	10	Refrigeration tank	PVC
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The type of analysis was set from cradle to gate, considering the raw material extraction phases necessary to configure the prototype facility and for WWTP effluent treatment and the processing phase. The inventory of the SERPIC prototype takes into account all the equipment making up the three sub-sections, together with the raw materials and energy consumed. The use of the effluents obtained from the SERPIC prototype is outside the limits of the system. A time horizon of 20,000 hours was assumed in which the plant will be in uninterrupted operation. A sensitivity study was carried out to analyse the influence of the useful life of the equipment that make up the prototype. For example, in the conservative scenario, a lifetime of 1,250 hours was chosen for the hydraulic equipment (pumping system and piping), while in the moderate and optimistic scenarios, this value increases to 5,000 hours and 10,000 hours respectively. This sensitivity study was carried out from the perspective of both environmental impacts (LCA) and costs (LCC). Therefore, the calculation of impacts and costs associated with the inventory of the installation took into account the replacements of equipment necessary for the installation to operate for those 20,000 hours.

Although life cycle analysis is a useful tool that provides information on the environmental impact of a process or service, the reality is that a sustainability study alone does not guarantee the market insertion of an emerging technology (as in the case of the SERPIC technology). In this context, the economic perspective is key, requiring the use of additional tools that allow to evaluate the economic viability of the process. Therefore, a life cycle cost assessment was carried out in order to support the environmental impact results of the LCA. To that aim, the life cycle inventory of the LCA was also used for the determination of the costs associated to the performance of the SERPIC process including the costs of raw materials, energy, and installation (construction, materials and maintenance). Regarding costs associated with the personnel of the plant, land purchases and location are out of the boundaries of the analysis.

The EU Regulation 2020/741 requires the implementation of a Water Reuse Risk Management Plan in reclamation facilities to ensure the safe use of reclaimed water and minimize the risks to the environment and human health. In this context, the FMECA has been applied to SERPIC technology. It consists in the identification of the different failure modes for the treatment components (i.e. leaks, ruptures, releases, malfunctioning, etc.), the corresponding consequences on the treatment performance (reduced removal of the target compounds) and the surrounding environment (release of compounds), thus deterioration of the quality of the final effluent with potential adverse effects on the environment and human health as well as unhealthy conditions within the treatment plant boundaries with potential risks for the workers.

The results of this analysis are reported in a table in terms of description of the identified failure modes and their effects. The risk is defined as the product between the frequency of the occurrence of a failure mode and the magnitude of its effects. According to the WHO recommendations (WHO, 2022), to assess and then prioritize the risk related to each failure mode, a score S_1 is assigned to the expected occurrence and a score S_2 to the magnitude. S_1 varies between 1 and 5 and S_2 may assume the following values: 1, 2, 4, 8 and 16, as shown in Table 4: the higher the occurrence, the highest S_1 and the highest the magnitude, the highest S_2 .

Table 4. Risk assessment matrix

Occurrence score, S_1	Magnitude score S_2				
	1 (insignificant)	2 (minor)	4 (moderate)	8 (major)	16 (catastrophic)
1 (rare)	1	2	4	8	16
2 (unlikely)	2	4	8	16	32
3 (possible)	3	6	12	24	48
4 (likely)	4	8	16	32	64
5 (almost certain)	5	10	20	40	80
Risk Score, S	<6	6–12	13-32	>32	
Risk level	Low	Medium	High	Very high	

In this way, the risk score is evaluated by **equation 1**:

$$S = S_1 \times S_2 \quad \text{eq. 1}$$

As reported in **Table 4**, the risk level is classified as low for S in the range 1-5; medium with S in the range 6 – 12, high for the range 13-32 and very high with $S > 32$. Those failure modes with the highest value of S correspond to the most critical ones. For these, an in-depth analysis of the existing preventive safety measures must be carried out to evaluate the capacity of the system to return the plant to normal operation, and if necessary, further (preventive and mitigative) safety measures must be implemented.

5 Results and Discussion

As mentioned in the methodology section, a useful life of the installation of around 20,000 hours was considered and this useful life was analysed from the perspective of 3 different scenarios (conservative, moderate and optimistic), in which equipment replacements were taken into account to guarantee the correct operation of the installation during its useful life.

Each of the sub-sections that make up the SERPIC prototype are shown below. **Figure 1 a)** corresponds to the ozone production unit, **Figure 1 b)** corresponds to the persulfate production unit and **Figure 2** corresponds to the water treatment unit, which includes the nanofiltration unit, the photoreactor and the disinfection tank.

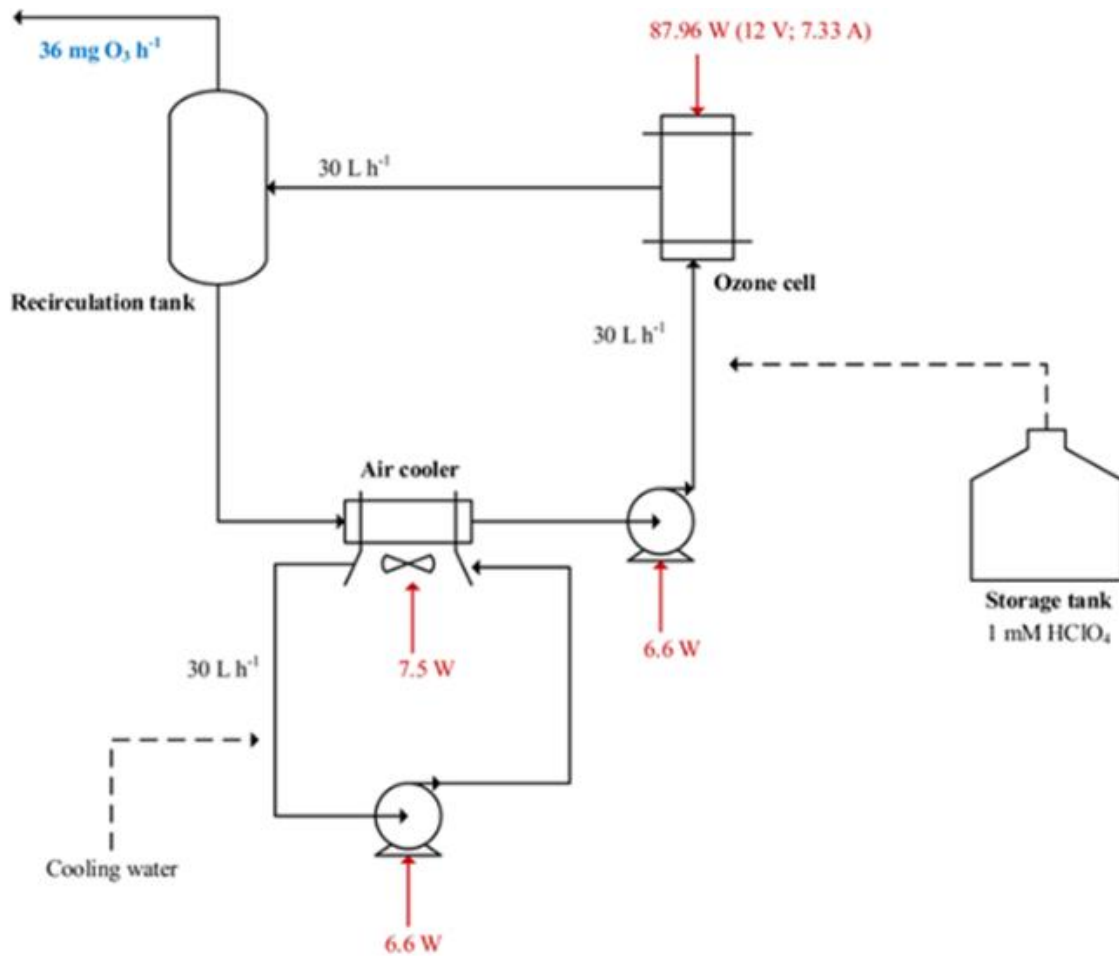


Figure 1. a) Ozone production unit.

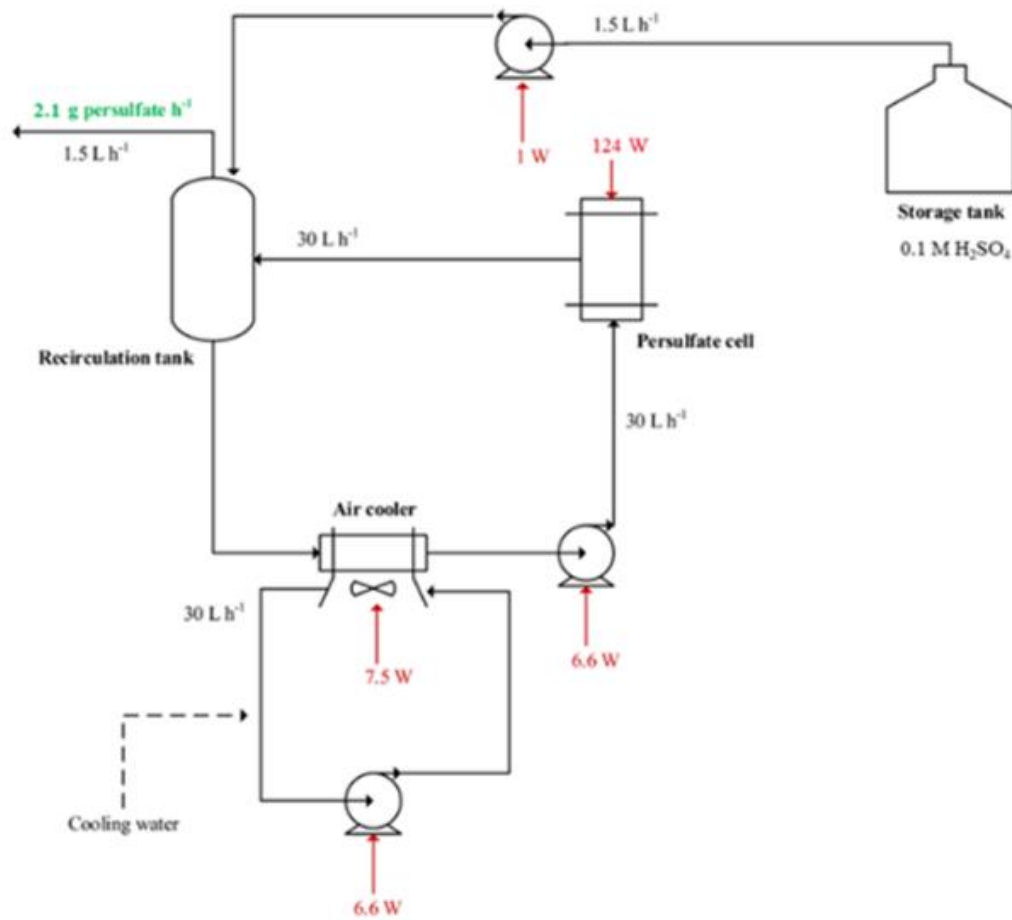


Figure 1. b) Persulfate production unit.

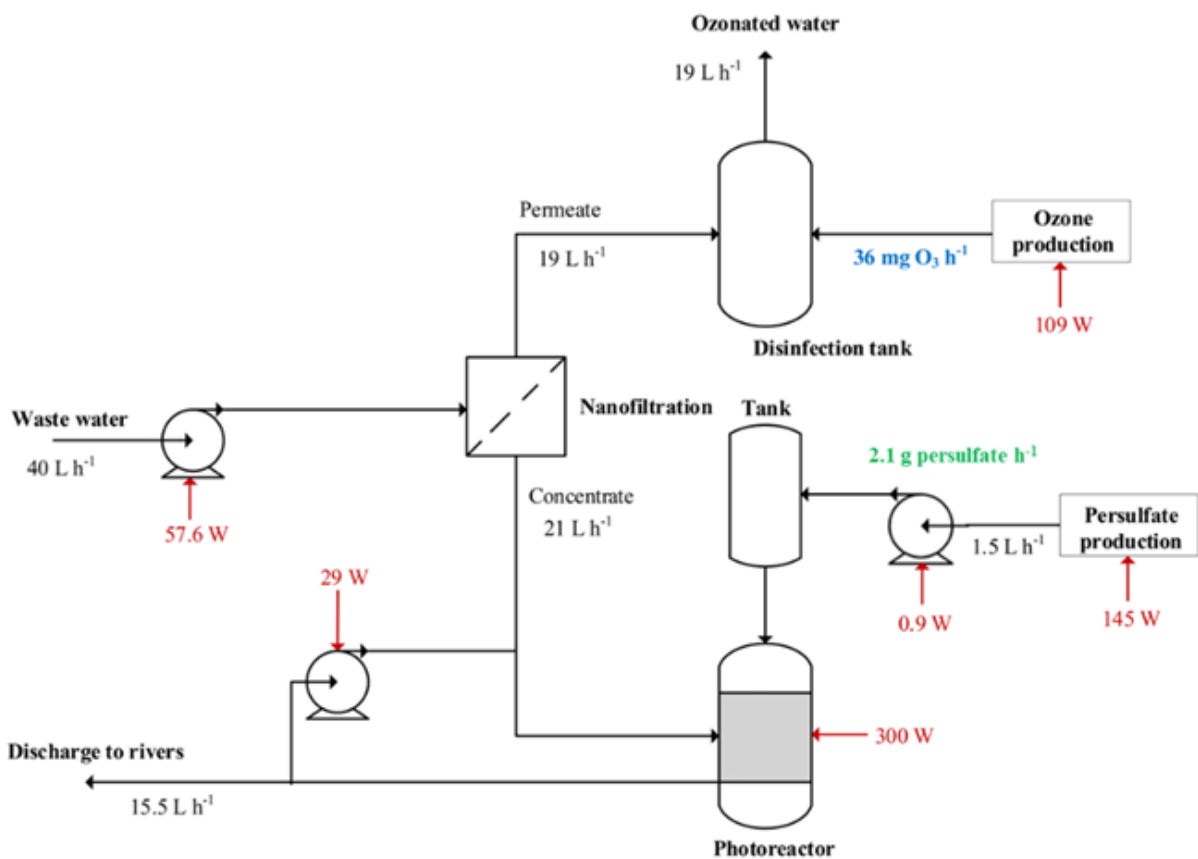


Figure 2. Water treatment unit

The indicators have been estimated for the treatment of one litre of water in all cases. The carbon footprint (calculated using IPCC methodology) for the conservative scenario is 10.2 g CO₂ per FU. 76% of this is due to energy consumption, as can be seen in Figure 3 a. The water footprint has been calculated using two methods AWARE and RECIPE. AWARE assesses the potential of water deprivation, to either humans or ecosystems, necessary to carry out the process over a period of time and RECIPE estimates water consumption. The water consumption of the plant is 0.68 L, 0.28 L and 0.22 L per FU for the conservative, moderate and optimistic scenarios respectively, calculated by RECIPE methodology. However, Figure 3 b shows the water used, calculated by AWARE methodology, which, although showing the same trend, is higher for all scenarios. The environmental impacts are expressed in comparative toxic units (CTUh) in case of the human toxicity i.e., the estimated increase in morbidity in the total human population per FU. For ecotoxicity, impact potentials are expressed in comparative toxic unit for freshwater ecosystem (CTUe), which provides an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per FU. As can be seen in Figure 3 c, d, the value for human toxicity is 8.7E-09 CTUh and for fresh water ecotoxicity is 0.14 CTUe for the conservative scenario.

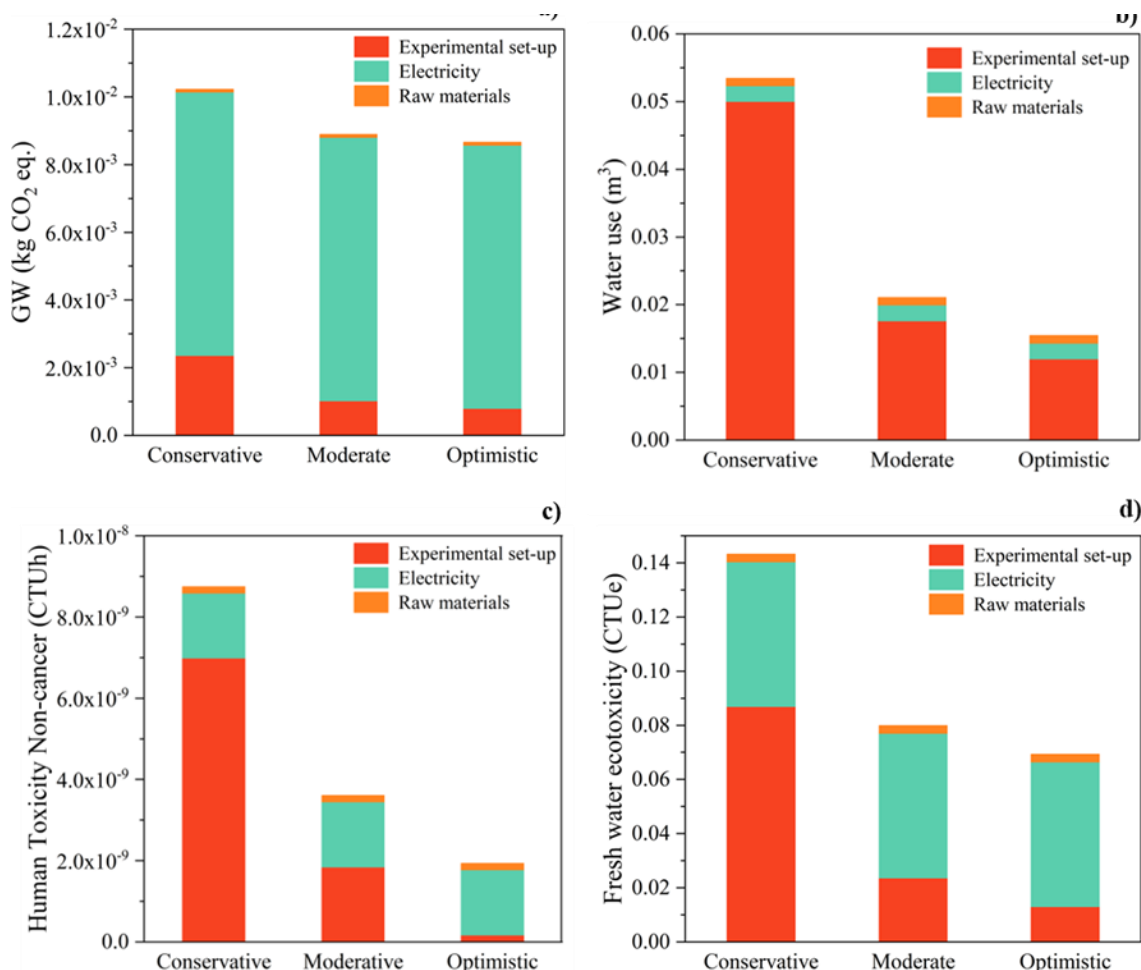


Figure 3 a) Global warming potential b) Water footprint c) Human Toxicity d) Freshwater ecotoxicity for the SERPIC water treatment at different lifetime scenarios. FU: L of water treated.

Figure 4 below shows the four impact categories, expressed in percentages, corresponding to the three sub-sections of the SERPIC prototype, the oxidant production and the water treatment units. It can be seen that, for the four impact categories studied, the treatment plant is the

subsection with the greatest impact, with a total impact of between 65 % and 90 %. Ozone production has the lowest impact, between 4 and 15 % of the total impact of the installation.

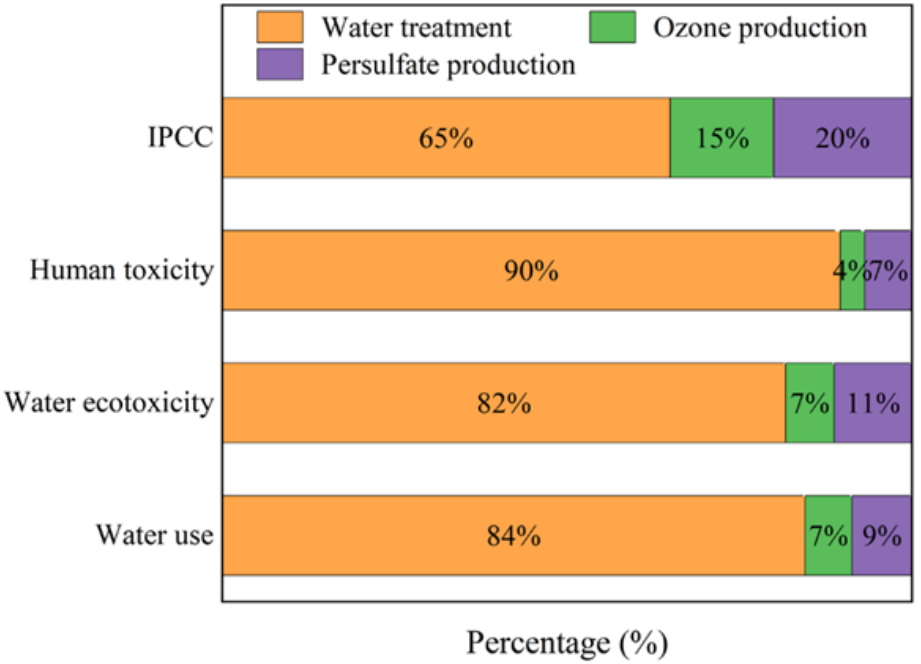


Figure 4. Impact categories of the overall installation by sub-sections expressed in percentage.

Finally, the LCC has been calculated. This is to the sum of all the costs required to operate the plant running for 20,000 hours per FU. This assessment includes the capital expenditures (CapEx) and the operational expenditures (OpEx). CapEx involves significant, long-terms investment in tangible assets that are depreciated over time (material and equipment), while OpEx refers to ongoing, recurring costs that are fully deducted in the year they are incurred, see Table 4. For the electricity cost, Eurostat biannual electricity price for non-household consumers in 2023 for the European Union has been used (EU-27, 0.174 €·kWh). Water consumption cost was estimated based on the average price of the tap water of 36 European cities for the year 2023, obtaining a value close to 3.57 €·m⁻³. Reverse osmosis deionisation treatment has been taken into account in the Capex and Opex calculations to condition the water used in the production of oxidants.

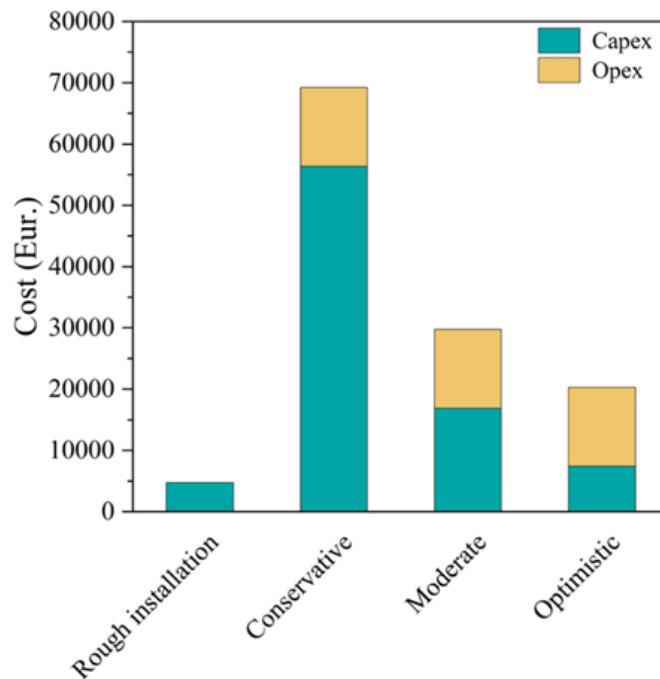


Figure 5. Economic study for the SERPIC water treatment at different scenarios. Lifetime: 20,000 h of operation.

Table 5. Lifetime operating costs of the SERPIC prototype.

OPEX		
Auxiliary services / Raw materials	Amount for 20000 h	Cost (EUR.)
Deionized water (L)	31049.20	111.05
Electricity (kWh)	13043.50	2269.57
Perchloric acid (g)	86.86	14.11
Sulfuric acid (kg)	294.24	10436.32

Figure 5 shows the importance of the sensitivity analysis performed, where the lifetime of the equipment determines if the Capex is close to 57,000 euros or reduced to 8,000 euros for the conservative and optimistic scenarios, respectively. The Opex is constant regardless of the scenario and has a value of 12.831 €. 81% and 17% of the Opex are due to the cost of sulfuric acid and energy, respectively. In all scenarios the cost of raw materials and energy is the same, 1.6 cents per FU. Therefore, the cost per litre of treated water using the SERPIC prototype varies from 8.7 cents, 3.8 cents and 2.6 cents depending on whether the scenario is conservative, moderate or optimistic, respectively.

The application of FMECA methodology to SERPIC technology resulted in the identified of 129 failure modes. **Table 6** contains the failure modes of the nanofiltration membrane module and their potential effects on the treatment systems. The same approach was applied to all the components of the SERPIC technology.

Table 6. Failures mode and their potential effects for the membrane module of nanofiltration unit of the SERPIC technology.

Unit	Component	Failure mode	Effects
	-	-	-
Nanofiltration unit	Membrane module	Pressure failure	A lower flow rate may go through the NF membrane. (Inadequate flow distribution between Route A and Route B)
		Breakage of the membrane module at the anchor points	No membrane filtration, the influent is inadequately treated (high concentration of <i>E. coli</i> , SS, CECs...)
		Breakage of the membrane module in other points	The permeate is inadequately treated and its quality is worse than the expected
		Membrane fouling	Pressure drop sharp increment, higher energy costs for going through, higher frequency of membrane cleaning
	-	-	-

The scores to the expected occurrence of the failure modes, S_1 , and to the magnitude of their effects, S_2 , were assigned, according to Table 4, on the basis of the opinion of experts working in similar treatments (at the University of Porto and at the research centre of NIVA, in Oslo), the personnel and researchers of the UCLM of Ciudad Real involved in the experimental campaign of the pilot plant in operation at their lab for 12-18 months, and fed with the secondary effluent of the local urban WWTP. The risk score, S , was evaluated by the eq.1 for the 129 identified failure mode. The distribution of the risk score S of the whole SERPIC treatment plant, shown in Figure 6, highlights that only two failure modes result in a very high risk level. These failure modes are reported in Table 7 together with their risk score.

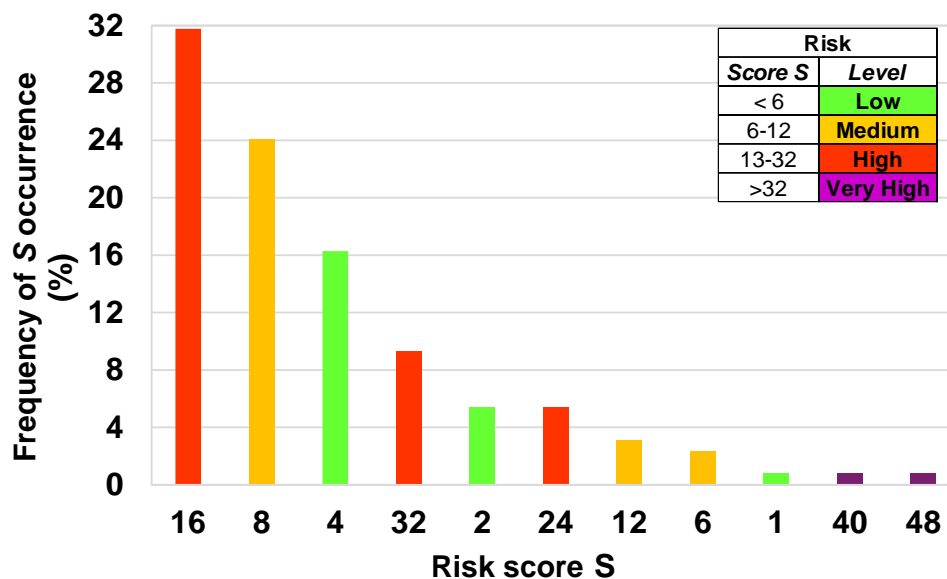


Figure 6. Frequency of the occurrence of risk score (S) for the 129 identified failure mode for SERPIC treatment train. The specific risk level for each score is represented by the different colors reported in the legend.

Table 7. The assessment of the risk score S for the two failure modes of the SERPIC technology characterized by the highest risk (very high risk).

Unit	Component	Failure mode	S_1	Effect	S_2	$S=S_1 \times S_2$
Photoreactor unit	UVC lamp	Aging	5	Lower persulfate activation and lower removal of CECs from the concentrate	8	40
	Persulfate feeding pump to photoreactor	The pump fails close when it should be open	3	Flow is pumped to the reactor. Hydraulic problems and persulfate solution wasted. No persulfate into the photoreactor, no degradation and disinfection of the effluent	16	48

In order to reduce the assessed risks, preventive safety measures must be (re-)evaluated, and if necessary further preventive measures must be adopted. Regarding the failure modes of Table 7, it is necessary to: *i)* evaluate if a more frequent replacement of UVC lamps must be scheduled, *ii)* guarantee an accurate control of operation of the persulfate feeding pump to photoreactor and *iii)* evaluate to place a flowmeter in the pipe to the photoreactor to control the persulfate feeding flow rate.

6 Publications and other dissemination activities

Rodríguez-Gómez, A., Castro M.P., Sáez C., Rodrigo, M.A., Fernández-Marchante, C.M. (2025) Electrochemical ozone production: Process Design, Life Cycle Assessment and Economic Analysis. Journal of Cleaner Production (ready to send)

Rodríguez-Gómez, A., Castro M.P., Sáez C., Rodrigo, M.A., Fernández-Marchante, C.M. (2025) Electrochemical Life Cycle Assessment and Life cycle costing of the electrochemical production of peroxosulfates (under development)

Fernández-Marchante, C.M., Rodríguez-Gómez, A., Castro M.P., Sáez, C., Lobato J., Rodrigo, M.A., (2025) Study on the sustainability of a pilot plant for the re-use of waste water using ozone and persulphate (under development)

Verlicchi, P., Grillini, V., Vilar, V., Castro, M. P., Sáez, C., Rodrigo, M.A., Krzeminski, P. (2024) Risk assessment in the case of reuse of reclaimed water – A proposed methodology. Oral presentation at SIDISA 2024 – Book of extended abstracts at the XII International Symposium on Environmental Engineering, Palermo, Italy, October 2024.

7 Literature

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Regarding the recent EU regulation on water reuse

Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse, Office of the European Union, (2020), <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741&from=EN>

EC Guidelines 2022/C 298/01, Commission Notice - Guidelines to support the application of Regulation 2020/741 on minimum requirements for water reuse, Office of the European Union, (2022),

Commission Delegated Regulation (EU) 2024/1765 of 11 March 2024 supplementing Regulation (EU) 2020/741 of the European Parliament and of the Council with regard to technical specifications of the key elements of risk management. OJ L, 2024/1765, 20.6.2024