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Deliverable Report
D4.3 Recommendations for policies

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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 was 1. September 2021. The project had a duration of 40 months and ended 31. December 2024.

The overall aim of the SERPIC project was 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 was applied to reduce CECs in its permeate stream by at least 90 % while retaining the nutrients. A residual disinfection using chlorine dioxide produced electrochemically was added to the stream used for crops irrigation (Route A). The CECs in the polluted concentrate (retentate) stream were 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 was set-up and evaluated for irrigation in long-term tests with the help of agricultural test pots. A review investigation of CECs spread was performed at four regional showcases in Europe and Africa. It included a detailed assessment of the individual situation and surrounding condition. Transfer concepts was developed to transfer the results of the treatment technology to other regions, especially in low- and middle-income countries.

2 Report summary

The deliverable collects the results of SERPIC project that could provide recommendations to national and European policy makers for updating policies related to wastewater treatment and reclaimed water reuse, and for future standards referring to organic and microbial CECs. Specifically, these results regard the development of (*i*) a methodology for selecting relevant organic and microbial CECs for monitoring plans, (*ii*) treatments train (Route A) alternative to conventional ones (i.e. depth filtration and UV disinfection) able to guarantee an effluent fulfilling the standards for a direct reuse (for instance those set by the European Regulation 2020/741), (*iii*) a methodology for the risk assessment of the developed technology (more in general the reclamation facility) in view of the implementation of the required water reuse risk management plan, and (*iv*) quaternary treatments alternative to the well-known and already implemented (ozonation and granular activated carbon filtration) for CECs removal from water before the discharge in surface water.

3 Deliverable description as stated in the Project Description

The deliverable will include the executive summary reports of task T4.5 as main results achieved by the development of the SERPIC solution which could be of interest for policy makers, regulations and standardization in case of direct reuse of reclaimed water and in case of control of the spread of CECs including ARGs/ARB.

4 Introduction

In SERPIC process chain, the secondary effluent is treated by a membrane nanofiltration (NF) producing a permeate which is then ozonated, with the ozone produced electrochemically (Route A). At the same time, the NF concentrate is oxidized in a photoreactor, by means of UV-C-activated persulfate, which is produced electrochemically (Route B). The final effluent may be reused for irrigation (Route A) and discharged into rivers (Route B).

The overall aim of the SERPIC project is to reduce the spread of organic and microbial CECs (including ARB and ARGs) and to provide an additional water sources for irrigation. Moreover, according to *Objective 3* of the project description, SERPIC has to develop methodologies and tools for monitoring health and environmental risk assessment and for the implementation of new reuse concepts, including new treatment technologies, as a basis for better policy and decision-making, for regulatory issues and new standards.

The SERPIC findings show that this objective has been achieved. Some of the developed methodologies as well as tested technologies are here discussed as they could be useful for decision-makers to develop further regulations for wastewater treatment and water reuse.

5 Results

The main results of SERPIC projects which can contribute to the implementation of further regulations for wastewater treatment and water reuse are:

1. the definition of a methodology for the selection of the most relevant CECs to include in monitoring programs in reuse projects in a specific area (polishing treatment evaluation; and environmental and human health risk assessment),
2. the development of alternative treatments process to guarantee quality standards for reclaimed water set by European Regulation 2020/741,
3. the development of a methodology to assess the risk as a first step of a water reuse risk management plan as required by European Regulation 2020/741,
4. the development of alternative treatments process to reduce the spread of organic and microbial CECs in the environment.

These results are described in the following sections.

5.1 Methodology for relevant CECs selection

The large number of CECs with different characteristics implies the need to select a short list of the most representative ones to be monitored. To this end, SERPIC project developed a new site-specific methodology to identify the list of relevant organic and microbial CECs to evaluate the performance of an end-of-pipe treatment in removing CECs. In addition, the methodology could be applied for the risk assessment for the soil and irrigated crops as well as for the surface and ground water due to surface runoff or percolation. For organic CECs, the selection is based on the Occurrence in the secondary effluent, the Persistence to the secondary treatment, the Bioaccumulation in organism tissue and the Toxicity to aquatic life (OPBT criteria): They are measured by the concentrations in the secondary effluent, the removal achieved in conventional activated sludge systems, the octanol–water partition coefficient (Log K_{ow}) and the predicted-no-effect concentration (PNEC), respectively. With reference to the area interested to the reclaimed water reuse, the methodology consists of: (*i*) the development of a dataset of CECs found in secondary effluent from literature or in-field investigations in the reference area; (*ii*) scoring of criteria between 1 (low environmental impact) and 5 (high environmental impact) based on threshold values established by literature and experts' judgment; (*iii*) ranking of CECs based on their final score (sum of the criteria scores); and (*iv*) the selection of the relevant CECs for the different needs.

For microbial CECs, after a literature review, the selection is based on clinical relevance, their higher detection frequency in secondary effluent, the antibiotic consumption patterns, and recommendations from national and international organizations.

For SERPIC technology, the methodology applied to the reference areas (Spain, Portugal, Italy and South Africa) resulted in a list of 30 relevant CECs. Six target compounds (diclofenac DIC, iopromide IOP, sulfamethoxazole SMX, venlafaxine VNLX, and, *E. coli*, *sul*1) were selected to be monitored during SERPIC prototype plant investigations. The other 24 compounds (21 organic CECs, one ARB and two ARGs) are recommended to be included in monitoring plans of reclaimed water project.

The described methodology is ready to be used by researchers and water treatment manufacturer to monitor the efficiency of a new end-of-pipe treatment technology in a specific area.

The results are published in the deliverable D1.1 – Target CECs (www.serpic-project.eu/) and in a scientific paper (Verlicchi et al., 2023), presented at the JRC webinar on Water Reuse (April 2024, the IWA international conference ICWRR2024 on water reuse in Palermo (June 2024) and the Italian workshop organized in November 2024 in Rimini to meet the stakeholders and discussed with them the main results.

5.2 Treatments in alternative to conventional ones for water reuse

In order to meet the quality standards defined by the European Regulation 2020/741 for water reuse, an additional end-of-pipe treatment step should be added to conventional WWTPs to improve the quality of the secondary effluent. A wide range of technologies are available, including both consolidated and under research and development. For agriculture reuse, the conventional processes are depth filtration and disinfection (e.g. by chlorination or UV) which are able to reduce suspended solids, bacteria and viruses (Metcalf and Eddy, 2007).

Route A of SERPIC technology, fed by the secondary effluent, consists of a membrane nanofiltration followed by an oxidation/disinfection by disinfected by electrogenerated ozone. These multibarrier approach acts as an end-of-pipe treatment producing a high-quality effluent suitable for irrigation. The analysis of the Route A effluent showed that its quality meets the standards set by the European Regulation 2020/741, see Table 1. Furthermore, SERPIC technology is able to reduce the concentrations of organic and microbial CECs from the secondary effluent, as required by the recently published revision of EU Urban Wastewater Treatment Directive (UWWTD, EU 2024/3019). Section 5.4 discusses the removal of CECs in detail.

After specific control tests, the supplier’s technicians found that the supplied membrane nanofiltration had an assembly problem which resulted in leakage during operation. This explained the removal of *E.coli* (Table 1), which was much lower than the expected values reported in other studies (among them Krzeminski et al., 2017).

Table 1: Concentrations of the specific parameters in the effluent of Route A. The last column shows the European Regulation 2020/741 quality standards for water reuse. LOD: limit of detection.

Parameter	**Route A**	**EU standard**
E. coli, CFU/100 mL	1.0 (< LOD) – 13.0	≤ 10
BOD_5, mg/L	< 5	≤ 10
TSS, ng/L	< 1	≤ 10
Turbidity, NTU	0.19 – 0.33	≤ 5

Thus, the SERPIC technology can be exploited as an alternative end-of-pipe treatment of secondary effluent for water reuse. The exploitation potential was investigated by means of a SWOT analysis. This approach is a decision support technique that leads to the identification of the factors relevant to the technology divided into four categories (strengths S, weaknesses W, opportunities O and threats T). Strengths and weaknesses are characteristics of technology that promise to be a winning or losing aspect, respectively. They are controlled by the decision makers (internal factors), and, for example, they may relate to technical performance and cost, or environmental sustainability. Opportunities and threats are future events that may have a positive or negative impact on technology. They cannot be directly influenced (external factors), but they must be monitored in order to take advantage of positive events and prevent negative ones. External factors can be divided into macro-environmental factors, which influence all human activities in general (political, economic, social, technological, environmental, legal and demographic factors) and micro-environmental factors, which include those closely related to the technology (existing competitors, new entrants, customers and suppliers).

The SWOT analysis was carried out following the approach described by Grillini et al. (2022). The internal factors (strengths and weaknesses) were selected based on the specific characteristics of the SERPIC prototype, thanks to the direct experiences of researchers of Universidad de Castilla-La Mancha (Ciudad Real), University of Porto, and NIVA (Oslo). The external factors identified in Grillini et al. (2022) were contextualized to water reuse, as this is the objective of the SERPIC technology. The feedback from the presentation of the SERPIC project results to stakeholders has also been the basis for the development of a useful SWOT matrix. The resulting matrix, divided into four quadrants (categories), is presented in Table 2.

Table 2: SWOT matrix for the SERPIC technology.

INTERNAL FACTORS	EXTERNAL FACTORS
Strengths (S) **S1** Water quality improvement **S2** Easy to control **S3** Dedicated treatment for NF concentrate **S4** No chemicals addition **S5** No waste production	**Opportunities (O)** **O1** Customer request (of a promising and valuable low cost (green) technology to be included in a dedicated treatment) **O2** European rules encourage water reuse **O3** European rules require CECs removal during urban wastewater treatment **O4** European Green Deal initiatives **O5** National policies (Implementation of national policies to reduce CECs in WWTP effluent) **O6** Public (farmer) interest in water reuse
Weaknesses (W) **W1** Variability of SERPIC prototype performance **W2** Safety concerns **W3** Operational problems **W4** Complex construction and equipment **W5** High energy demand	**Threats (T)** **T1** Variation of CECs concentration in secondary effluent **T2** Attention to aquatic life **T3** Other CEC treatment technologies as its main competitors **T4** Socio-economic concerns

It emerges that SERPIC technology presents significant strengths, but also some non-negligible weaknesses. This technology can be adopted as end-of-pipe treatment in order to reuse the final effluent for irrigation and with the implementation of specific actions it will be possible to mitigate some weaknesses and consequently limit the threats with the strengths.

The results are included in deliverables D1.7 – Performance of final prototype version, D2.8 – Prototype final version and in D3.3 – Transfer concepts (www.serpic-project.eu/), have been presented at the SIDISA conference in Palermo (October 2024), and are included in technical and scientific papers (under progress).

5.3 A risk assessment methodology for the development of a water reuse risk management plan

For ensure the safe use of reclaimed water, European Regulation 2020/741 requires to develop a water reuse risk management plan for the water reuse system (WWTP + water reclamation + supply +distribution system+ crops and environment) including the assessment and management of risks for the environment and the human/animal health.

As emphasised by the European Delegated Regulation 2024/1765, the complex development of a water reuse risk management plan should be based on a multidisciplinary and structured approach. Existing international guidelines or standards, such as the WHO Sanitary Safety Plan (SSP) can be used to develop such a plan (WHO, 2022).

As a first step of SSP, SERPIC project carried out a methodology based on Failure Mode, Effects, and Criticality Analysis (FMECA) to identify the failure modes of the treatment components (i.e. malfunctions, leaks, ruptures, releases, etc.) and to assess their main potential effects on the quality of the final effluent and its suitability for irrigation needs, with consequences for the environment and the human health. According to WHO recommendations, a score is assigned to the occurrence of a failure mode and the magnitude of its effects. The risk is classified into different levels based on the risk score, which is the product of the two defined scores. Failure modes with the highest risk score value represent the critical events (with very high risk levels). For these, a thorough analysis of the existing preventive safety measures must be carried out to assess the ability of the system to return to normal operation, and if necessary, to take additional safety measures to mitigate the effects and thus reducing the risk.

The methodology can be used by the parties involved in the water reuse system to perform a detailed analysis of the treatment train and to assess the risk of component failure modes, as a first part of a water reuse risk management plan required by European Regulation 2020/741.

The results are reported in the deliverable D3.2 – LCA and LCC results (www.serpic-project.eu/), were presented at the SIDISA conference in Palermo (October 2024) and will be published in a scientific paper (under progress).

5.4 Alternative treatments to those current applied for CECs removal

The EU's Water Framework Directive (WFD, EU 2000/60) regulates the protection and sustainable management of all water bodies with the goal of achieving "good status". The UWWTD (EU 2024/3019), which covers the collection, treatment and discharge of wastewater, supports the WFD. In addition to the secondary treatment (removal of biodegradable organic matter), the recent UWWTD states that largest WWTPs (with 150,000 population equivalent or more) must upgrade the tertiary treatment to fulfill the more severe limits of nitrogen and phosphorus and implement a quaternary treatment in order to remove micropollutants.

Ozonation and adsorption on granular (GAC) or powdered activated carbon (PAC) have been shown significant reduction of a wide spectrum of CECs in national and international studies. In recent years, several full-scale plants of these technologies have been built in Switzerland (FOEN, 2015) and Germany (Bourgin et al., 2018, Itzel et al., 2020).

SERPIC process chain can be compared with the technologies already implemented in WWTPs to remove CECs from effluents. The main advantage of SERPIC is that two effluents are produced. After treatments of Route B, the effluent is suitable for release into rivers. Since the effluent of Route A complies with EU quality standards for reuse, which are more restrictive than the limit set in the UWWTD for discharge, it can be discharged into aquatic environment if necessary. In both Routes, SERPIC treatment chain is able to reduce organic and microbial CECs concentration below the limit of detection of the instrument (see Table 3), except for VNLX. Excluding VNLX, the discharge in surface water of Route B effluent, or Route A if necessary, will not increase its CEC content.

Table 3: Concentrations of the selected CECs in the two SERPIC water effluents (Route A and Route B). LOD: limit of detection.

Parameter	**Effluent concentration (range)**	
	Route A	**Route B**
DIC, ng/L	45.0 (< LOD)	45.0 (< LOD)
IOP, ng/L	140 (< LOD)	140 (< LOD)
SMX, ng/L	20.0 (< LOD)	20.0 (< LOD)
VNLX, ng/L	40.0 (< LOD) – 99.0	339 – 455
***E. coli,* CFU/100 mL**	1.0 (< LOD) – 13.0	1.0 (< LOD)
***sul1,* n° copies/mL**	1.0 (< LOD) – 2.35	1.0 (< LOD) – 39.4

The removal of organic CECs by nanofiltration is based on size exclusion, i.e. organic CECs with molecular weight in the range 300–1000 g/mol are typically rejected by the membrane (Rizzo et al., 2020). Therefore, CECs are not degraded but accumulate in the concentrate. SERPIC prototype plan not only showed a reduction of organic CEC concentration by at least 80% (DIC < IOP < SMX < VNLX) in membrane nanofiltration, but also includes a Route B for the treatment of concentrate aiming to overcome the problem of CECs accumulation.

In the disinfection step, the SERPIC project electrochemically generates ozone in an electrolyser equipped with a proton exchange membrane and diamond electrodes. The main advantages are lower energy requirements and direct ozone production without using pure oxygen (Rodríguez-Peña et al., 2021). These solutions may be a promising alternative to the conventional ozone production from air or oxygen.

Regarding Route B, the photoreactor was designed to activate persulfates, which were produced electrochemically, and to achieve the removal of CECs from the nanofiltration concentrate, as it provides a good fluid-dynamic pattern. The effect of activated persulfate depends on the physicochemical characteristics of CECs and the applied dosage, in fact, for DIC, SMX, IOP and *E.coli* the removal was completed (>96%) whereas for *sul*1 and VNLX the removal, 69–99.5% and 56–70% respectively, was influenced by the dosage of persulfate applied.

According to the SERPIC results, the developed technology is a promising alternative for CECs removal. To make the SERPIC prototype plant feasible for full-scale applications in WWTPs, the scale needs to be increased by five orders of magnitude, as the technology operates at a flow rate of 34 L/h whereas a medium WWTP typically has a flow rate of 10^6 L/h.

The results are reported in deliverables D1.7 – Performance of final prototype version and D2.8 – Prototype final version (www.serpic-project.eu/) and in technical and scientific papers (under progress), and presented at the SIDISA conference in Palermo (October 2024).

6 Publications and other dissemination activities

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7 Literature

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