

Urban wastewater treatment plants as resource hubs: evaluating circularity and sustainability of nutrient recovery and water reuse

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ARTICLE INFO

Keywords:

Circularity indicators
Life cycle analysis
Scenario analysis
Treated wastewater reuse
Resource recovery

ABSTRACT

Wastewater treatment plants (WWTPs) are evolving from pollution control facilities into resource recovery hubs, aligning with circular economy principles. However, assessing their transition requires robust methodologies that integrate environmental, economic, and circularity dimensions. This study aims to evaluate the sustainability and circularity performance of a WWTP in Cyprus upgraded with additional treatment stages to recover nutrient-rich sludge for fertilizer and treated water for irrigation. To achieve this, a combined methodological framework was applied, incorporating standardized Circularity Assessment (based on ISO 59,004), Life Cycle Assessment (LCA), and Life Cycle Costing (LCC). Circularity was assessed using a dual-indicator approach: “resource flow indicators” (covering material, energy, and economic flows) and “circular actions indicators” (capturing process optimization, repurposing, cascading, and regeneration). Environmental and economic impacts were quantified using LCA and LCC, respectively, while sensitivity analyses explored the effects of renewable energy integration and process simplification. Results show that while the upgraded WWTP enhances circularity through increased resource recovery and high-value product generation, it also incurs higher environmental impacts and operational costs due to energy-intensive technologies (distillation, reverse osmosis, and nanofiltration), increasing the impacts in values that can achieve +60 % in some impact categories. Sensitivity scenarios demonstrated that reducing energy demand and increasing renewable energy use can improve sustainability outcomes, with the higher average impact reduction achieving -20 %, though often at the expense of circularity performance. The study highlights the trade-offs between maximizing resource recovery and minimizing environmental and economic burdens, emphasizing the need for optimized process design and supportive policy frameworks to enable WWTPs to function as effective circular economy enablers. The findings show that advanced treatment technologies enhance circularity through increased resource recovery, but also entail elevated energy demands and limited economic viability. While frameworks like ISO 59,004 support multidimensional assessment, further methodological development is needed to guide sustainable decision-making.

1. Introduction

To move towards a more circular and sustainable production and consumption model, it is not enough to only develop new technologies and production processes and integrate them into value chains as alternatives to conventional models; it is also necessary to modify current economic systems in a way that maximizes their sustainability and circularity potential as sustainable development and/or circular

economy transitions occur. This is pertinent for the wastewater treatment sector, which conventionally combines various types and configurations of technologies in order to ensure that the treated wastewater is safe for, at least, its disposal in the environment (Ding, 2023; Pariente et al., 2020). Wastewater treatment is a process considered essential for social communities to protect human and environmental health, however, the inefficiency of wastewater treatment processes can lead to significant negative effects in terms of environmental impact, such as

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eutrophication or ecotoxicity (Preisner et al., 2021; Szklarek et al., 2021). Even though there have been many innovative technologies developed in the last decade, the sector is risk averse and relies on a reliable but archaic asset base, limiting the potential for replacement or retrofitting of WWTPs with more sustainable and circular technologies.

Looking beyond just wastewater treatment systems, and moving towards a circular economy, wastewater treatment plants can also be seen as resource recovery factories with cascading production strategies, where not only the wastewater is sufficiently treated, but also its value is recovered and regenerated by producing useful products (Ye et al., 2021). Through this CE lens, wastewater should not be considered only as a waste stream, but also as a valuable resource. Wastewater contains high-added value compounds such as nutrients and carbon-based compounds (Kundu et al., 2022) that can be recovered, valorized and reused into the wastewater treatment plant (in terms of energy and chemicals recycling) (Rodrigues et al., 2024; Zarei, 2020) or other value chain processes (such as the agricultural sector) (Penserini et al., 2024; Jaramillo and Restrepo, 2017). In addition, treated water can also be reused as irrigation water for agriculture, when its quality is sufficient, significantly reducing the need to use the natural resource as well as the pressure on the water treatment sector (Ofori et al., 2021).

Therefore, wastewater treatment can be considered as a critical sector which promotes the transition from linear to circular models, by producing high value-added products from waste, reducing the consumption of pristine resources (Hernández-Chover et al., 2023; Obaideen et al., 2022). Increasing the capacity of wastewater treatment plants to recover these resources can contribute significantly to reducing environmental impacts and improving economic efficiency, among other benefits (Ruffi-Salís et al., 2022; Faragò et al., 2021).

Even if the integration of technologies for the valorization of compounds present in wastewater aims for a greater circularity of the process, the circular value must be measured, and the consequences of circular strategies must be measured by carrying out techno-economic and environmental analyses to confirm that the development of these new process stages actually leads to a sustainable improvement of the economic system. Usually, the most advanced technologies or those that achieve greater resource recovery are very costly and generally very energy intensive (Kato and Kansha, 2024; Li et al., 2017), which can have a negative impact on the sustainability potential of the plant. Therefore, it is necessary to investigate these potential trade-offs and consider them in the decision-making process, as they are critical for the viability of up- and out-scaling innovative technologies.

It is in this context that this research article is framed, in which, on the one hand, an alternative scenario for the valorization and treatment of wastewater has been presented, based on the integral recovery of available resources, and, on the other hand, a series of sustainability and circularity indicators have been selected in order to analyze in detail the effects of this alternative scenario, both positive and negative. To this end, the Life Cycle Assessment framework (ISO, 2006a) was used to develop a Life Cycle Cost (LCC) (ISO, 2017) to evaluate the economic viability of the alternative model and its benefits compared to the conventional one, followed by an Environmental Life Cycle Assessment (LCA) (ISO, 2006b) to quantify the environmental impacts and provide the environmental profile of both alternatives. In addition, a set of circularity indicators were selected to measure the extent to which the facility improves the circulation of resources and minimizes the generation of waste, following the guidelines of ISO 59,004 and 59,020 (ISO, 2024). By combining these three perspectives, this research report provides a robust framework for evaluating the sustainability and circularity potential of an innovative wastewater treatment solution to enhance resource recovery. This combined assessment could guide decision-making, engineers and policy makers to design and implement wastewater treatment facilities that go beyond pollutant removal and actively contribute to a more sustainable and circular water sector. Therefore, promoting the development of wastewater treatment facilities that prioritize sustainability, and circularity can lead to significant

environmental and economic benefits, supporting the transition to a more resource efficient and resilient future.

By modelling new technologies focused on water reuse and nutrient recovery, this research provides a promising alternative to transform WWTPs into sustainable resource hubs contributing to the circular economy, thus promoting long-term sustainability and circularity in the water sector.

On the other hand, there is a lack of combined and multicriteria analysis of wastewater treatment technologies in the literature, mostly focused on sustainability analysis but not including circularity evaluation, as it could be seen in the following **Table 1 – SM (Supplementary Material)**, which includes some of the most recent articles analyzing wastewater treatment technologies under a sustainability and/or circularity approach.

In this regard, the main research questions (RQs) that this research aims to address are: (RQ1) how the integration of advanced treatment technologies influence the circularity performance?; (RQ2) what are the environmental trade-offs associated with the increase of energy composition in circular-oriented WWTP processes; (RQ3) to what extent the inclusion of advanced treatment technologies demonstrate economic feasibility; (RQ4) how standardized circularity frameworks, as ISO 59,004, can help to assess the multidimensional impacts (i.e. resource flows, value generation, etc.) of WWTPs to move forward to cascading production systems?

The proposed methodological procedure introduces a novel integration of LCC, LCA and circularity indicators to holistically evaluate the sustainability, circularity and economic feasibility of wastewater treatment processes. This multidisciplinary combination allows for a more comprehensive decision-support framework that goes beyond conventional assessments focused solely on environmental or cost parameters. Besides, circularity is not still widely considered as a methodology for analyzing new process schemes, being LCA or techno-economic assessments the ones more used. Another key point of this combined and multidisciplinary method is that in existing LCA and LCC research reports, can lead to suboptimal choices in complex decision environments, as those are neglecting material circularity, water recovery value, and the trade-offs between cost and resource efficiency. In this regard, the proposed method addresses this gap by integrating technical performance indicators and resource valorization metrics into the sustainability assessment.

2. Methodology: combining circularity and sustainability

The circularity and sustainability assessment performed in this research article is based on the systematic framework proposed by Renfrew et al. (2024a). The framework could be considered as the basis for standardizing the circularity assessment of wastewater resources and moreover, it integrates sustainability indicators. It starts with the system definition consisting of defining the assessment goal and scope. Then, the second step is based on the system mapping and the modelling for describing the wastewater processes and the system being assessed. Aspects that are required for modelling and data collection are important to be described as those establish the necessary information about the wastewater processes and system. These two previous steps enable the procedure of the next methodological step, based on the intrinsic circularity assessment. This step consists of the resource flow classification and the identification of the circular actions, as well as the circularity indicators, with the objective of measuring the intrinsic circularity performance of the wastewater process. The last step is based on the selection and quantification of the sustainability indicators, which enables the measurement of the consequences of implementing circular actions in the wastewater process. To this end, this research report integrates two separate assessment stages: first, the circularity assessment, combining the analysis of the resource flow classification and circular actions; and secondly, the economic and environmental analysis following the life cycle assessment approach. This systematic

framework was applied to assess a retrofit system integration in a wastewater treatment plant (WWTP) located in Larnaca, Cyprus.

2.1. System definition: mapping and modelling

The Larnaca WWTP has a treatment capacity of 100,000 person equivalents, with a maximum rate of 18,000 m³/day. It is a conventional wastewater treatment facility, consisting of five main stages (pretreatment, biological treatment, membrane bioreactor (MBR), disinfection stage, and sludge treatment) (Fig. 1). This represents the Base Case Scenario (BCS) of the assessment, enabling the benchmarking of results.

The main characteristics of the capacity and influent/effluent parameters of wastewater treatment plant located in Larnaca are presented on Table 1.

On the other hand, in terms of energy needs and sources, as Cyprus is a region with more than 300 days of sunshine, the use of solar energy seems to be an efficient and interesting way to move towards a less polluting value chain by reducing the dependence on fossil resources for energy production (Kassem et al., 2024; Agathokleous and Kalogirou, 2021). Specifically, the use of solar energy was planned for the drying of sewage sludge, which will reduce energy consumption and maintenance activities, thus reducing operating costs (Rada et al., 2014; Salihoglu et al., 2007). In this regard, the WWTP system has a contribution of 40 % of renewable energy from a photovoltaic system.

The WWTP of Larnaca produces around 3500,000 m³/year of treated wastewater, which is sold for local irrigation purposes in agriculture and recreational areas. The use of treated wastewater for irrigation contributes by reducing pressure on local freshwater sources. However, the treated wastewater has a high salinity content (Table 2 – **Supplementary Material**) which can cause soil salinization which results in diverse problems such as reduction of agricultural productivity by impacting the plant water uptake and altering the physiology and anatomy of plants. Controlling the salinity content of treated wastewater for irrigation is important to avoid soil salinization (Ofori et al., 2021). As a result of this issue, a system composed of multiple processes is integrated in the WWTP in order to remove the salinity content from the treated wastewater. In addition, by integration/retrofitting multiple units in the WWTP, phosphorus, sodium chloride (NaCl) and mixed salt (magnesium and calcium) are consequently recovered. Therefore, the goal of the assessment is to measure the circularity and sustainability performance of the process integration in the Larnaca WWTP. The performance of the integration scenario is going to be compared with the Larnaca WWTP without the integration in order to enable the identification of benefits and hotspots of the system integration.

The alternative case scenario (ACS) consisted of a retrofitting system which is integrated between the MBR and the disinfection stage. The retrofitting system is composed of six technologies: (1) biophree reactor [BP], (2) nanofiltration [NF], (3) reverse osmosis [RO], (4) low-

Table 1

General data and characteristics of Larnaca WWTP (WTE-EVN group, 2025; Avramidi et al. (2023)).

WWTP capacity		Chemical and biological parameters		
Person equivalents	100,000		Influent	Effluent
Daily rate (2027 scenario)	18,000 m ³ /d	BOD ₅	6000 kg/d	≤ 5 mg/L
Daily rate (2047 scenario)	22,000 m ³ /d	Suspended solids	6000 kg/d	≤ 5 mg/L
Actual maximum rate	18,000 m ³ /d	Total nitrogen	1300 kg/d	≤ 5 mg/L
Actual average rate	750 m ³ /d	Total phosphorous	350 kg/d	≤ 1 mg/L
		Salinity content	2500 mg/L	

temperature evaporator [LTE], (5) multi-effect distillation [MED] and (6) crystallization [CRY] (Fig. 2).

The BP process aims to adsorb the phosphorous contained in the treated wastewater in order to be further valorized for, as example, the production of a phosphorus fertilizer that could be applied to the agricultural sector. Apart from the objective of recovering the phosphorous, this first stage is also intended to prevent biofouling situations in the next stage which is NF. Divalent ions (i.e. Mg²⁺ and Ca²⁺) present in the liquid effluent of the BF process are removed in the NF unit, while the monovalent ions like Na and Cl are retained in the following RO unit. The NF concentrate flows into the LTE unit in order to recover a Mg and Ca salt, while the RO concentrate flows into the MED unit to recover water from the concentrate generating a brine stream rich in sodium and chlorine, to be afterwards crystallized in the crystallization unit. In this CRY stage, NaCl crystal salts are produced to be further used in the chlorination step, replacing the conventional supply of NaCl required for the disinfection unit in the WWTP. The water recovered by the RO, LTE, MED and CRY are mixed, and 6 % of the treated wastewater is pumped in order to remineralize the recovered water to sufficient levels for irrigation.

The system was operated at pilot scale under the scope of the project H2020 WATER-MINING (grant agreement No. 869,474), and operational data was collected for up-scaling the system in order to fit the WWTP operational conditions, as well as to develop the process inventories, required for the sustainability and circularity assessments. The up-scaling of the system was based on specific calculations that describe each process.

2.2. Circularity - resource flow classification

This step aims to assign circular and linear characteristics to all resources in the assessed system, thus improving the traceability and

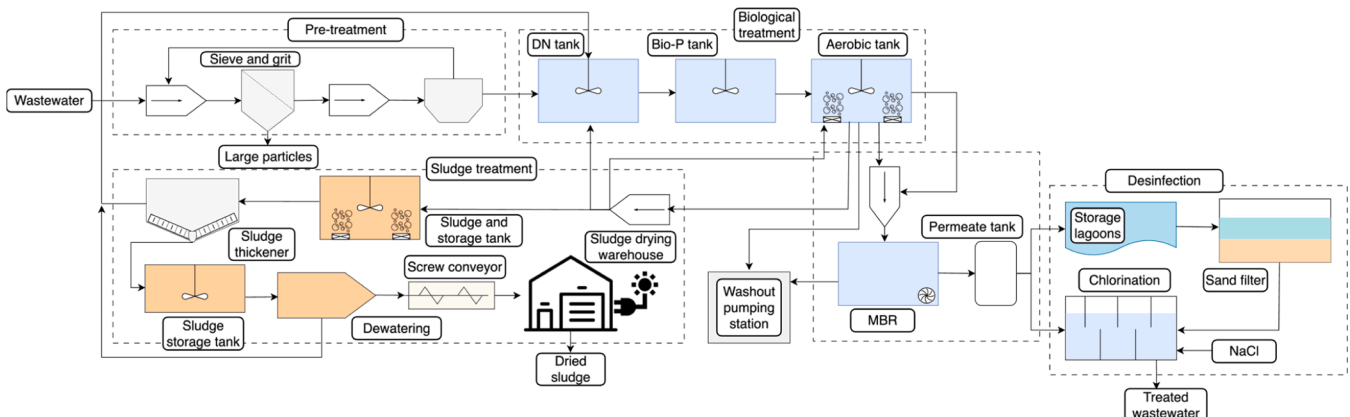


Fig. 1. BCS flow diagram.

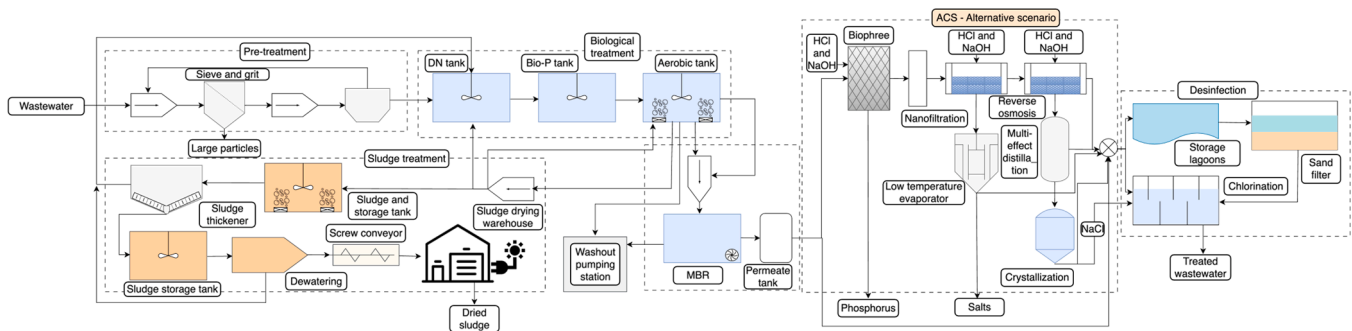


Fig. 2. ACS flow diagram.

transparency of the circularity indicators calculation (Renfrew et al., 2024b). The circularity classification was made based on the components of the wastewater flows (i.e. water, phosphorus, sodium, chlorine, magnesium and calcium), which are defined below.

- The water content in wastewater flow is classified as *circular* because it has the potential to be recovered for restoration of a water body or for other uses such as recycling, reuse and reclamation (Renfrew et al., 2024b).
- The water content in the chemicals flows, such as FeCl_3 , is classified as a *linear* flow because it comes from a virgin source, and it is not being recovered. But, one exception is for phosphorus, as there is a fraction that comes from natural sources, which is classified as *circular* (e.g. human urine and faeces), and the other fraction that comes from non-natural sources is classified as *linear* (e.g. detergents, food additives, etc.) (Renfrew et al., 2024b).
- Ions in chemicals are classified as *linear* as those are obtained from non-renewable sources. Ions in wastewater are also classified as *linear* as they are unintentional inputs from saline intrusion.
- In terms of water discharge, the water content is *circular* if "water is discharged at the required regulatory quality and used to restore a freshwater body (in the same catchment) or reused for purposes that reduce freshwater withdrawals (recycling, reuse, reclamation) by supplementing the needs of other processes" (Renfrew et al., 2024b). If this is not the case, then the treated effluent from a WWTP cannot be considered a regenerative action and is classified as *linear* until water quality or effluent concentrations are improved to meet the critical load.
- For the classification of phosphorus discharges, those are classified as circular flows if "effectively recovered for controlled release to land (for fertilisation or conditioning) or used in products to extend the life of nutrients in the human system, replacing the use of virgin resources". If that is not the case, then those are classified as linear, as those discharges "are not effectively recovered and are released to the environment (atmosphere, water and soil) in a way that is harmful to the natural functioning of ecosystems".
- The ions in the products are classified as a *circular* flow if they provide the function of the products (Ribeiro et al., 2025). On the contrary, if the content of the ions exceeds the permitted composition to ensure water quality, then those are classified as a *linear* flow.

2.2.1. Resource flow indicators

The resource flow indicators are used in order to analyze the intrinsic circularity, encompassing three categories: resource, energy and economic. The resource category is focused on the flows of the scenario under evaluation, and it includes 4 indicators: *circular inflow*, *circular outflow*, *total circular flow* and *recovery efficiency*. The circular flow indicators are calculated based on the definitions provided in the resource flow classification (Section 2.3). The energy category aims to analyze the use of renewable energy along the process, measuring the

performance of the renewable energy integration, thus implying the calculation of one indicator: *renewable energy integration*. Lastly, the goal of the economic category is to measure the efficiency and effectiveness of the system within an economic perspective, evaluating the relationship between the total revenues obtained and the linear resource consumption, using the indicator *circular material productivity*, thus showing the process of decoupling linear consumption for circular product production.

2.2.2. Circular actions indicators

Circular actions are implemented with the purpose of adding, retaining and recovering value, which is often lost due to linear and unsustainable activities (Ribeiro et al., 2025). Four circular actions were identified from integrating the system in Larnaca WWTP: (1) *optimization*: aims to increase product generation and reduce resource consumption; (2) *repurposing*: NaCl is recovered in the CRY process and used in the disinfection step which aims to reduce fresh NaCl input; (3) *cascading*: recovering of nutrients and minerals from outflows; and (4) *prevention*: improving the quality of the treated wastewater for irrigation purposes, which also avoids further soil salinization.

Table 2 presents the circular action indicators chosen in function of the identified circular action, as well as the type of value they imply, the equations used for its calculation and the description of the scores reflect. For the process optimisation action, three indicators were selected. The *system productivity indicator* measures the capacity of a WWTP to produce products (e.g. irrigation water) and/or co-products (e.g. NaCl). The *energy and chemical demand indicators* measure the amount of these resources required to generate the products and co-products. The calculation of the indicator also considers internal energy and chemical production by the system.

The *Waste Eco-efficiency (WEE) indicator* measures the economic value of repurposing flows with the intention of generating revenues and reducing waste. The previous CE action only occurs due to the cascading scheme of the system integration, and it is quantified by using the *nutrients and minerals recovery indicator*, measuring the amount recovered from the wastewater. Lastly, for prevention action, the quality of water leaving the ACS and the BCS are compared as the goal of the system integration is to reduce the salinity content.

2.3. Sustainability assessment – environmental and economic methods

2.3.1. Life cycle cost (LCC) analysis

The LCC methodology is a well-recognized framework that aims to comprehensively evaluate the total costs associated with a product, process and/or service, which is standardized in the ISO 15,686, including the guidelines on how it should be developed (Gluch and Baumann, 2004). The economic performance indicators required to develop a LCC could be divided into three main categories, which are associated with the life cycle stages, namely: construction, operation and maintenance, and end-of-life costs. The expenses on the "construction stage" includes the construction costs, land purchase costs, energy

Table 2

Resource flow indicators for circularity assessment including its equations for calculation and CE actions, indicators and equations used in the circularity assessment.

Resource flow indicators				
Category	Indicator	Equation	Description	
Resource	Circular inflow (%)	$\frac{\text{Mass circular inflow}}{\text{Total mass inflow}} \cdot 100$	Higher value means more circular flows or recovery efficiency	
	Circular outflow (%)	$\frac{\text{Mass circular outflow}}{\text{Total mass outflow}} \cdot 100$		
	Total circular flow (%)	$\frac{\text{Circular inflow} + \text{circular outflow}}{2}$		
	Recovery efficiency (%)	$\left[1 - \left(\frac{\text{Mass inflow} - \text{mass outflow}}{\text{Mass inflow}} \right) \right] \cdot 100$		
Energy	Renewable energy contribution (%)	$\frac{\text{Renewable energy}}{\text{Total energy consumption}} \cdot 100$	Higher value means higher renewable energy contribution	
Economic	Circular material productivity (€/kg)	$\frac{\text{Total revenues}}{\text{Total mass of linear inflow}}$	Higher value means less dependency of the revenues from linear flows	

Circular action indicators				
Circular action	Value	Indicator	Equation	Description
Process optimization	Added value	System productivity (kg/kg)	$\frac{\text{Mass of wastewater}}{\text{Mass of products and co-products}}$	Closest to one more circular
		Energy demand (kWh/kg)	$\frac{\text{Total energy} - \text{self-produced energy}}{\text{Mass of products and co-products}}$	Lower value means more circular
		Chemical demand (kg/kg)	$\frac{\text{Chemical demand} - \text{self-produced chemicals}}{\text{Mass of products and co-products}}$	Lower value means more circular
		Waste eco-efficiency (WEE) (€/ton)	$\frac{\text{Total revenues}}{\text{Total mass of waste}}$	Higher the value, better the performance
Cascading	Value recovery	Nutrients recovery (kg/ton)	$\frac{\text{Mass of nutrients}}{\text{Mass of wastewater}}$	Higher value means more circular
		Minerals recovery (kg/ton)	$\frac{\text{Mass of minerals}}{\text{Mass of wastewater}}$	
		Irrigation water quality	Quality parameters: [PO ₄], [Na], [Cl], [Mg], [Ca], [SO ₄]	
Prevention	Regeneration of lost value			Lower salinity concentration values, better quality

costs and labor costs associated with this life cycle stage. “Operation and maintenance category” comprises consumables, such as chemicals and energy, equipment maintenance, licensing fees, administration, and training and personnel activities expenditure. Lastly, end-of-life stage comprises all costs related with the activities required for the management and treatment of the final flows, residues and/or emissions derived from processes.

With the above cost values for each of these stages, the CAPEX (Capital Expenditure) and the OPEX (Operational Expenditure) scores are calculated (**Table 3 – Supplementary Material**), which are required to proceed with the evaluation of economic feasibility. Regarding the CAPEX values of the BCS, it should be mentioned it was not considered, neither analyzed, due to a lack of data. This equipment was acquired approximately a decade ago by the WWTP owners, and it should have depreciated significantly since then.

The viability of the process is assessed by the calculation of the net present value (NPV), benefit-cost-ratio (BCR) and payback period (PP). The NPV represents the difference between the present value of cash inflows and the present value of cash outflows over the system boundaries considered for the scenarios (Swan, 2015). The BCR shows the relationship between the relative costs and benefits of the scenario being evaluated, expressed in monetary or qualitative terms. If BCR is lower than 1, then the investment option generates losses, if it is equal to 1, the means that it could be neither profitable nor lossy, while if BCR is higher than 1, the investment option is profitable (Frej et al., 2021). Lastly, the PP represents the number of years required to recover the investment. If the PP is higher than the expected project lifetime, then benefits will not be achieved in the active phase of the project, thus representing that the scenario under evaluation is not profitable (Wu and Buyya, 2015). **Table 4 – Supplementary Material** presents the equations required to calculate all the economic indicators previously defined.

2.3.2. Environmental analysis with LCA

The life cycle assessment (LCA) method is used to evaluate the environmental performance of BCS and ACS. This assessment

methodology is based on the ISO 14,040 and ISO 14,044 (Finkbeiner et al., 2006), which includes the guidelines, to develop an accurate and adequate environmental analysis. This methodological framework consisted of the development of four main stages: (1) goal and scope definition – in which the system boundaries and the functional unit of the analysis is selected and defined, also the allocation approach, if needed –, (2) inventory analysis – based on the recompilation of all the input and output data of the scenario under assessment–, (3) impact assessment – selection of the impact method for converting the environmental releases to impact categories. Also, in this stage, the environmental performance profile is obtained – and (4) results interpretation – focused on the analysis of the results obtained, identification of the main contributors of the environmental profile, known as hotspots, and proposal of sensitivity assessments aiming at improving the environmental sustainability potential of the scenario under analysis.

This analysis is based on an attributional LCA, considering as system boundaries were a gate-to-gate, which entails all the stages from the WWTP entry gate to the exit gate, thus being focused on the wastewater treatment and valorization process. As a functional unit, 1 m³ of treated wastewater was selected. In this regard, the data required for the construction of the life cycle inventory has been gathered from the information collected from WATERMINING project partners, which developed the design and modelling of the scenarios. **Table 3 – Supplementary material** includes the inventory of the proposed wastewater system. The ACS had multiple functions because it treats urban wastewater and recovers secondary materials, therefore, the mass allocation method was applied. In this regard, an additional functional unit has been considered, a product-based one, focused on the analysis of the environmental loads per total amount of effluent products. The ReCiPe 2016 hierarchist method, at MidPoint level, has been selected to calculate environmental impacts: Global warming (GW), Stratospheric ozone depletion (SOD), Ionizing radiation (IR), Ozone formation, human health (OFHH), Fine particulate matter formation (FPMF), Ozone formation, terrestrial ecosystems (OFTE), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial

ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNCT), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS) and Water consumption (WC). On the other hand, once obtained the environmental profile of the ACS, hotspots will be identified aiming at developing appropriate sensitivity analysis for improving the environmental sustainability potential of the alternative WWT technological procedure.

3. Results and discussions

3.1. Resource flow indicator calculation

Regarding the circularity analysis based on resource flow indicators, the integration of the ACS does not imply a difference when compared to the conventional scenario (BCS), in terms of the *circular inflow* indicator (Fig. 3A). This is because the integration does not impact the inflow of the WWTP, only the outflow. Therefore, the linear and circular

properties of the resource inflows are maintained. Moving onto the evaluation of the *circular outflow* and *flow indicators*, significant differences are observed between both scenarios, being ACS the one that provides better circular performance, given the addition of the remineralization stage, in which the concentration of the compounds in the outflow are considerably reduced, thus improving the quality of water to be used for irrigation activities.

When evaluating the scores obtained for the *recovery efficiency* indicators, it could be observed that the ACS enhances and promotes the recovery of ions, which are not recovered in the BCS, as could be seen on Fig. 3B. The integration of the additional stages enables to develop a more circular wastewater treatment process in which there is a commitment to the recovery of high-added value compounds. Only in the case of the phosphorus, the recovery percentage achieved is the same, with the difference that, in the BCS, the phosphorus is in the treated wastewater for irrigation and in the ACS, it is recovered in the BP as fertilizer. On the other hand, it should be mentioned that when analyzing the water recovery indicator, a lower value is obtained for the

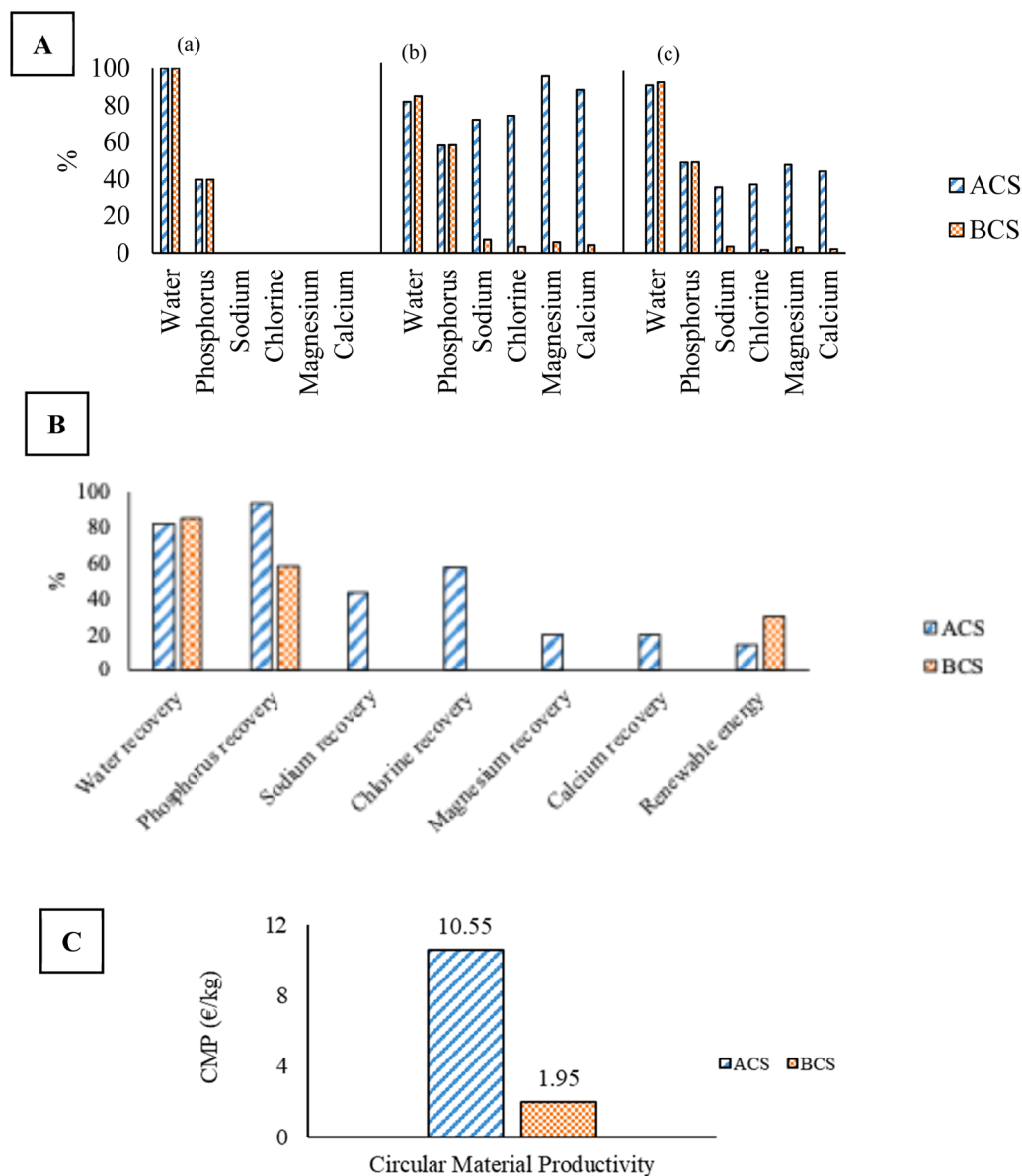


Fig. 3. A. Resource flow indicators: Circular inflow (a), outflow (b) and total flow indicators (c) for water and ions (sodium, chlorine, magnesium, calcium and sulphate). B. Recovery efficiency indicator for water and ions (sodium, chlorine, magnesium, calcium and sulphate), and renewable energy indicators. C. Circular Material Productivity (CMP) indicator.

ACS, given a small water fraction is lost in the integrated additional stages. Finally, the *renewable energy* indicator shows a lower value for the ACS. This decrease is not due to a reduction in the use of renewable energy, but to the fact that the addition of process stages implies a higher energy consumption and therefore a lower contribution from renewable energy to the total energy demand.

For the economic-related indicator category, a comparison can be made between the two scenarios, with more promising values for ACS in the case of the *Circular Material Productivity* indicator, which measures the total revenues over the total mass of linear inflow (Fig. 3C). The fact of betting on a greater valorization of the process streams, as in the case of chemical recirculation or fertilizer production, implies, in a way, the transformation of a water treatment plant into resource recovery hub, into a cascade production, which implies higher revenues given the recirculation/production of high-added value compounds. Concretely, the ACS scenario provides a score of 10.55 €/kg of linear consumption, while BCS only amounts to a value of 1.95 €/kg. This differences on the scores obtained for the indicator demonstrates how opting for a higher recovery, and thus for a higher circularity process, of the available compounds in the wastewater flows implies a real benefit and transition towards a circular economy. In addition, the recirculation of NaCl in the disinfection step decouples the WWTP from purchasing virgin NaCl from the market, thus moving from a linear to a circular production model, which also implies an effect over the *Circular Material Productivity* score obtained.

3.2. Circular action indicator calculation

Regarding the "circular action indicators", the values obtained for the BCS and ACS are shown in Table 3. Similar values are observed between BCS and ACS in the case of "system productivity", although for ACS 1.22 kg of wastewater is required to produce 1 kg of products and co-products, while 1.18 kg for BCS. Despite the small difference, this is due to the fact that the ACS recovers less water for irrigation than the BCS reference system, since by integrating more intermediate stages of the process, some water losses occur. A less promising value is also obtained in the case of "energy demand" for the ACS, which requires

Table 3

Circular action indicators results for BCS and ACS scenarios.

Circular action indicators				
Category	Value	Indicator	BCS	ACS
Process optimization	Added value	System productivity (kg/kg)	1.18	1.22
		Energy demand (kWh/kg)	1.07	2.11
		Chemical demand (kg/kg)	2.10 ⁻⁴	1.10 ⁻⁴
Repurposing	Value retention	Waste eco-efficiency (€/ton)	8683.32	15,962.38
Cascading	Value recovery	Minerals recovery (kg/ton)	–	2.4
		Nutrients recovery (kg/ton)	0.2	0.2
Regeneration	Regeneration of lost value	Irrigation water quality (mg/L)	[P]: 1.52	[P]: 0.10
			[Na]: 566.12	[Na]: 84.58
			[Cl]: 900.19	[Cl]: 140.14
			[Mg]: 85.02	[Mg]: 5.65
			[Ca]: 461.10	[Ca]: 30.64
			[SO ₄]: 535.11	[SO ₄]: 35.56

twice as much energy as the BCS. This is due to the integration of more processes in ACS which are energy intensive like MED and TC. However, in terms of chemical requirements, the ACS requires less chemicals compared to the BCS due to the recovery of NaCl and its reuse in the disinfection step, thus implying the optimization of consumed chemicals in the WWTP.

When analyzing the categories of "repurposing", "cascading" and "regeneration", ACS shows significant improvements in terms of eco-efficiency (since ACS has nearly doubled the revenue generated from the same amount of waste compared to the BCS and, at the same time, lower mass of waste is produced), value retention (thanks to the recovery of nutrients and also to the recycling of NaCl along the process, which reduces the need to purchase fresh NaCl, with the environmental and economic impact that this has) and value recovery (achieving a value of 2.4 kg of nutrients recovered per ton of wastewater treated in the process). To this end, it could be stated that the implementation of a cascading system significantly contributes to increasing revenues, while maintaining the same nutrient recovery indicators value in both scenarios. In addition, the quality of the output "water for irrigation" is also improved, as the concentration of the salinity content is significantly reduced compared to the reference case, which reduces the risk of crop salinization and allows the water to be used for a wider group of crops. The only drawback is the amount of phosphorus in the irrigation effluent, which is very low in ACS compared to the reference system.

3.3. Economic indicator calculation – LCC analysis

The results of the LCC analysis are shown in Table 4, while the contribution of each step of the proposed alternative scenario (ACS) is shown on Fig. 1- **Supplementary Material**. The ACS shows consistently higher OPEX than BSC, mainly due to the high energy consumption, maintenance costs and plant overhead costs, which amounts to 1002 k€/y, 458 k€/y and 108 k€/y, respectively. Looking deeper into the reasons for these high costs, in terms of energy requirements, the MED stage is the one entailing the higher contribution – 47 % of total energy demand. Distillation processes are one of the major energy consumers in the industry, due to its high heat demand and the limited potential for heat recovery due to its configuration (Jobson, 2014). However, in addition to MED, there is also another important step that requires a high amount of energy, the NF+RO configuration. This filtration stage contributes to 45 % of all energy requirements of the ACS. Although the nanofiltration process has been shown to be a more appropriate filtration technology to reduce investment costs, with an average energy consumption of 0.8–1.5 kW/m³ (Wafi et al., 2019), the reverse osmosis technology uses around 2.5–4 kW/m³, making the combined filtration method highly energy demanding (Kim et al., 2019). In order to reduce electricity costs, an analysis should be conducted aiming at using only the nanofiltration technology instead of combining it with a reverse osmosis unit or optimizing the process to reduce energy demands.

With respect to the maintenance costs, the same stages/processes/units are the ones implying higher contributions, 33 % for MED and 32 % for NF+RO stage. The significant costs of these stages are mostly due to the following reasons: (1) all these technologies are exposed to high temperatures and saline environments, which implies higher materials corrosion, degradation and scaling, thus requiring regular servicing activities and replacement to maintain the quality and efficiency of the wastewater treatment processes (Li et al., 2024; Go et al., 2019), (2) MED, NF and RO are quite complex technologies that require specific and specialized maintenance procedures, as well as an adequate monitoring and automation processes, which are more expensive (Othman et al., 2021), (3) for the NF+RO stage, the membrane system is prone to fouling and scaling given the accumulation of salts, organics, particular matter, and others, thus requiring special and regular cleaning (Philibert et al., 2024) and, (4) concretely for the RO technology, the high pressures required for this type of filtration implies an increased likelihood for mechanical failures, which results in higher maintenance activities

Table 4

Life Cycle Cost analysis of the alternative wastewater treatment and comparison among the economic indicators obtained the alternative case scenario (ACS), and comparison with the base case scenario (BCS). Code: an arrow in red color means worst score for the ACS, while an arrow in green color means better score for the ACS compared to the BSC.

Items			ACS
Capital expenditures (CAPEX)			
Equipment costs (€)	BP	2716,066	15,281,167
	NF+RO	5107,969	
	LTE	1293,935	
	MED	4948,187	
	CRY	1215,011	
Installation cost (€)	25 % equipment cost	3820,292	
Building, process and auxiliary cost (€)	20 % equipment cost	3056,233	
Land cost (€)	6 % equipment cost	916,870	
Direct cost (€)		23,074,562	
Indirect cost (€)		3461,184	
Fixed capital investment (€)	15 % of direct costs	26,535,747	
Working capital (€)	20 % of direct costs	3980,362	
Total annual CAPEX (€)		30,561,109	
Operational expenditures (OPEX)			
Maintenance (€)	3 % direct costs	458,435	
Operating supplies (€)	5 % maintenance	22,922	
Operating labor (€)	15 % OPEX	322,871	
Direct supervisory and labor (€)	15 % operating labor	48,431	
Laboratory charges (€)	15 % operating labor	48,431	
Patents and royalties (€)	3 % annual OPEX	64,574	
Fixed charges (€)	3 % annual OPEX	64,574	
Plant overhead costs	5 % annual OPEX	107,624	
Chemical costs (€)	-	153,996	
Energy costs (€)	¹ BCS + ACS	2099,160 ¹	
Total annual OPEX (€)		3391,018	
Comparison between base case (BSC) and alternative (ACS) scenarios			
Economic indicator	BSC	ACS	Comparison
CAPEX (k€)	-	30,516	-
OPEX (k€/y)	1167	3391	ACS ↑ - Negative for ACS
Revenues (k€/y)	3123	3373	ACS ↑ - Positive for ACS
NPV (k€)	31,911	-29,842	ACS ↓ - ACS not economic viable
BCR (-)	1.68	-0.01	ACS ↓ - ACS not economic viable

and, if needed, also replacement of the membranes (Tayeh, 2024).

With regard to the OPEX, this corresponds to a value of 2152 k€/y for the additional treatment system, which, together with the costs associated with the other stages of the wastewater treatment system, amounts to 3391 k€/y, which is approximately 3 times higher than the value for the BCS. The incorporation of advanced technologies for further valorization of the compounds present in the wastewater streams implies these higher operating costs, but it is expected that these investments will be justified by the long-term economic benefits, given the reduction of waste streams and the production of high-added value products for the agricultural sector, such as water for irrigation and fertilizers.

Focusing on CAPEX, which includes equipment costs, installation costs, auxiliaries and land costs, it is also observed that the two largest contributors to OPEX are also the ones on CAPEX. The reasons are similar, being advanced treatment technologies, their acquisition costs are also more expensive, as well as installation, requiring specialized knowledge of the technology. On average, the percentage contribution of the MED and NF+RO stages to the CAPEX is 32 % and 33 %, respectively, while on the contrary, the ACS stage with the lowest percentage contribution over CAPEX is CRY, with 8 %. A comparison with the BCS could not be made in this case because the CAPEX value for the existing treatment plant is not available. However, the results achieved for the ACS are expected to be significantly higher than for the BCS, due to the increased number of equipment in the wastewater treatment

facility and its technological complexity.

Lastly, when analyzing the revenues obtained for the BCS and ACS, those are higher for the latter, but not sufficient to overcome the operational costs of the process, thus obtaining a negative NPV, meaning that, as it is, the ACS process is not economically viable. Given this, it is necessary to optimize the process and even determine which steps can be avoided while maintaining the quality of the treated water and other products obtained, in order to reduce the associated costs and provide a technology that can be implemented in water treatment systems in the short term. Alternative scenarios have been developed and discussed in Section 4.4 with the aim of reducing costs and increasing the viability potential of the proposed ACS.

3.4. Environmental indicator calculation – LCA approach

The environmental scores obtained for each of the impact categories are included in Table 5 for both BCS and ACS scenarios, considering as the functional unit the treatment of 1 kg of wastewater. Besides, in order to evaluate the impact of each of the additional stages proposed for further valorization and recovery, also the impact values per product obtained are analyzed. In this regard, it should be defined the amount of each outflow produced per kg of wastewater treated: 170 mg of fertilizer sludge/kg of treated wastewater, 0.8 kg of irrigation water/kg of treated wastewater, 1.7 g of Mg+Ca/kg of treated wastewater, 0.7 g of NaCl recovered/kg of treated wastewater and 1.3 mg PO₄³⁻/kg of treated wastewater.

When analyzing the environmental impact per process, considering 1 m³ of treated wastewater as a functional unit, it could be seen that in almost all the impact categories, the development of ACS results in higher environmental impacts compared to BCS. There are only two exceptions, specifically for the impact categories ME and FET, where the development of ACS implies a reduction of 9 % and 6 %, respectively, compared to BCS. On the contrary, higher differences are observed in the impact categories of FPMF, OFTE, OHFF, TA, TET and LU, with an average increase in environmental impact that amounts to +60 %. On the other hand, the lowest differences are observed for MRS, WC, HNTC and MET, with an average of +17 %.

Proceeding to an alternative functional unit, in this case focused on the analysis per obtained effluent products, two alternative comparisons have been made in terms of BCS and ACS scenarios, since they have in common the production of sludge fertilizer and irrigation water. As can be seen in Table 5 and Fig. 2B-Supplementary Material and 2C-Supplementary Material, the opposite happens when considering this functional unit, with BCS being the one with the higher impact per type of product obtained in the majority of the impact categories evaluated. Higher differences are observed when analyzing the irrigation water, since in 15 out of 18 impact categories the BCS is the one with the lower impact, and with significant differences. The most striking are the impact categories GW, SOD, OFHH, PMPF, OFTE, TA and FRS, where the impact for ACS is more than 50 % higher compared to BCS, while for others, such as MET, HNTC and MET, similar environmental scores were obtained for both scenarios. On the contrary, it should also be mentioned that ACS implies a better environmental performance in the case of ME, FET and MRS impact categories, with reduced contribution values that amount to 15 %, 16 % and 5 %, respectively.

For the other product, the sludge fertilizer, the differences between the two scenarios are not as significant, but there is an important improvement for the ACS. In this case, it is the ACS scenario that leads to lower impacts in most of the categories evaluated, especially FET, MET, HCT, HNCT, HNCT, MRS and WC, where the impacts are reduced by -39.58 %, -33.30 %, -27.10 %, -33.21 %, -35.51 % and -22.85 %. Another positive aspect is that the average increase in impact compared to BCS is less than 10 %, so considering that ACS achieves a higher recyclability of products, a higher valorization and a lower need for external resources, it is considered that for the specific case of fertilizer production, ACS has a *high to very high* potential.

Table 5

Environmental scores per impact category considering both BCS and ACS scenarios. Also, analysis of the impacts in terms of the type of product obtained for the ACS scenario. Acronyms: SF (sludge fertilizer) and IW (Irrigation water). Color code: in the stages that are comparable (whole process, SF and IW), comparison between ACS and BCS impact effects is analyzed, highlighting in orange the scenario with the higher environmental effects.

Acronym	Per process (1 kg of treated wastewater)		Per outflow produced (per kg)							Unit
	BCS	ACS	SF		IW		Mg+Ca	NaCl	PO ₄ ²⁻	
			BCS	ACS	BCS	ACS	ACS	ACS	ACS	
GW	6.77·10 ⁻⁴	1.74·10 ⁻³	1.35·10 ⁻⁷	1.48·10 ⁻⁷	6.77·10 ⁻⁴	1.49·10 ⁻³	4.11·10 ⁻⁶	2.51·10 ⁻⁴	7.38·10 ⁻¹⁰	kg CO ₂ eq
SOD	4.71·10 ⁻¹⁰	1.26·10 ⁻⁹	9.77·10 ⁻¹⁴	1.07·10 ⁻¹³	4.89·10 ⁻¹⁰	1.08·10 ⁻⁹	2.96·10 ⁻¹²	1.79·10 ⁻¹⁰	5.37·10 ⁻¹⁶	kg CFC11 eq
IR	9.78·10 ⁻⁶	1.71·10 ⁻⁵	2.03·10 ⁻⁹	1.65·10 ⁻⁹	1.01·10 ⁻⁵	1.51·10 ⁻⁵	3.94·10 ⁻⁸	2.02·10 ⁻⁶	8.67·10 ⁻¹²	kBq Co-60 eq
OFHH	2.19·10 ⁻⁶	5.94·10 ⁻⁶	4.54·10 ⁻¹⁰	4.98·10 ⁻¹⁰	2.27·10 ⁻⁶	5.06·10 ⁻⁶	1.40·10 ⁻⁸	8.61·10 ⁻⁷	2.49·10 ⁻¹²	kg NOx eq
FPMF	1.39·10 ⁻⁶	3.70·10 ⁻⁶	2.88·10 ⁻¹⁰	3.12·10 ⁻¹⁰	1.44·10 ⁻⁶	3.16·10 ⁻⁶	8.72·10 ⁻⁹	5.33·10 ⁻⁷	1.56·10 ⁻¹²	kg PM2.5 eq
OFTE	2.21·10 ⁻⁶	6.00·10 ⁻⁶	4.58·10 ⁻¹⁰	5.04·10 ⁻¹⁰	2.29·10 ⁻⁶	5.12·10 ⁻⁶	1.42·10 ⁻⁸	8.69·10 ⁻⁷	2.52·10 ⁻¹²	kg NOx eq
TA	4.27·10 ⁻⁶	1.17·10 ⁻⁵	8.85·10 ⁻¹⁰	9.78·10 ⁻¹⁰	4.42·10 ⁻⁶	9.95·10 ⁻⁶	2.75·10 ⁻⁸	1.70·10 ⁻⁶	4.88·10 ⁻¹²	kg SO ₂ eq
FE	6.46·10 ⁻⁸	1.07·10 ⁻⁷	1.34·10 ⁻¹¹	1.09·10 ⁻¹¹	6.69·10 ⁻⁸	9.48·10 ⁻⁸	2.46·10 ⁻¹⁰	1.21·10 ⁻⁸	5.60·10 ⁻¹⁴	kg P eq
ME	1.89·10 ⁻⁸	1.72·10 ⁻⁸	3.92·10 ⁻¹²	2.83·10 ⁻¹²	1.96·10 ⁻⁸	1.67·10 ⁻⁸	3.59·10 ⁻¹¹	3.99·10 ⁻¹⁰	1.40·10 ⁻¹⁴	kg N eq
TET	2.90·10 ⁻³	6.87·10 ⁻³	6.02·10 ⁻⁷	6.04·10 ⁻⁷	3.01·10 ⁻³	5.90·10 ⁻³	1.61·10 ⁻⁵	9.52·10 ⁻⁴	3.02·10 ⁻⁹	kg 1.4-DCB
FET	9.62·10 ⁻⁶	9.03·10 ⁻⁶	1.99·10 ⁻⁹	1.21·10 ⁻⁹	9.97·10 ⁻⁶	8.42·10 ⁻⁶	1.97·10 ⁻⁸	5.85·10 ⁻⁷	6.15·10 ⁻¹²	kg 1.4-DCB
MET	1.42·10 ⁻⁵	1.65·10 ⁻⁵	2.93·10 ⁻⁹	1.96·10 ⁻⁹	1.47·10 ⁻⁵	1.50·10 ⁻⁵	3.69·10 ⁻⁸	1.47·10 ⁻⁶	9.94·10 ⁻¹²	kg 1.4-DCB
HCT	1.26·10 ⁻⁵	1.80·10 ⁻⁵	2.61·10 ⁻⁹	1.90·10 ⁻⁹	1.31·10 ⁻⁵	1.60·10 ⁻⁵	4.09·10 ⁻⁸	1.94·10 ⁻⁶	9.69·10 ⁻¹²	kg 1.4-DCB
HNCT	1.99·10 ⁻⁴	2.34·10 ⁻⁴	4.13·10 ⁻⁸	2.76·10 ⁻⁸	2.07·10 ⁻⁴	2.13·10 ⁻⁴	5.24·10 ⁻⁷	2.09·10 ⁻⁵	1.41·10 ⁻¹⁰	kg 1.4-DCB
LU	1.12·10 ⁻⁵	2.37·10 ⁻⁵	2.32·10 ⁻⁹	2.20·10 ⁻⁹	1.16·10 ⁻⁵	2.06·10 ⁻⁵	5.53·10 ⁻⁸	3.11·10 ⁻⁶	1.10·10 ⁻¹¹	m ² a crop eq
MRS	7.89·10 ⁻⁷	8.48·10 ⁻⁷	1.63·10 ⁻¹⁰	1.05·10 ⁻¹⁰	8.17·10 ⁻⁷	7.78·10 ⁻⁷	1.88·10 ⁻⁹	6.83·10 ⁻⁸	5.34·10 ⁻¹³	kg Cu eq
FRS	1.88·10 ⁻⁴	5.03·10 ⁻⁴	3.90·10 ⁻⁸	4.26·10 ⁻⁸	1.95·10 ⁻⁴	4.29·10 ⁻⁴	1.19·10 ⁻⁶	7.22·10 ⁻⁵	2.13·10 ⁻¹⁰	kg oil eq
WC	2.17·10 ⁻⁶	3.20·10 ⁻⁶	4.49·10 ⁻¹⁰	3.46·10 ⁻¹⁰	2.25·10 ⁻⁶	2.87·10 ⁻⁶	7.23·10 ⁻⁹	3.19·10 ⁻⁷	1.81·10 ⁻¹²	m ³

A further assessment was made by taking into account all products and recycling achieved through the development of the ACS, as shown in Table 5. The largest environmental contribution is undoubtedly irrigation water. It is important to mention that, in order to make this comparison between stages, the mass allocation approach was applied, which consequently implies a greater impact on irrigation water, since it is the one obtained in larger quantities. Among the other products, the one that stands out for its environmental impact is the recovery and recirculation of NaCl, due to the need to use membrane systems and distillation units, which are very energy-intensive equipment, resulting in a greater environmental impact.

3.5. Sensitivity assessment – alternative scenarios for improving sustainability

Looking to improve LCC, LCA and circularity parameters and to provide a wastewater treatment strategy that is economically feasible, environmentally sustainable and with high circularity potential, alternative scenarios are proposed:

1. Scenario ACS-1: BP stage not being considered, therefore no phosphate recovery, as testing procedures were performed, and no biofouling was observed on the NF and RO units during the system operation.
2. Scenario ACS-2: BP, NF, MED and CRY stages removed as those processes demand a high level of thermal energy, thus implying important environmental contribution. In this sense, water is only recovered from the RO stage, while salts by the LTE one.

3. Scenario ACS-3: Increase on the share of renewable energy enough for achieving a global warming impact, CO₂ eq. emissions, equal to the BCS.

Once analyzed the scores obtained by the aforementioned alternative scenarios (Table 6) for the ACS, it could be stated, in terms of economic perspective, the lowest CAPEX value is obtained by implementing the ACS-2, which was expected, as the most number of stages are removed from the wastewater treatment system, achieving capital expenditures that are less than a half in comparison with ACS. On the contrary, by considering ACS-3, no variances are observed in this value, while for ACS-1, a reduction of 22 % on CAPEX score is obtained. In terms of operational costs, OPEX, costs reductions are observed in all the proposed alternative scenarios, concretely with a reduction percentage that amounts to -7.53 % for ACS-1, -61.02 % for ACS-2 and -74.07 % for ACS-3. Analyzing the values, two main outcomes could be stated in this regard: (1) the opting for renewable energy really implies an economic benefit, being able to reduce the operational costs by more than 70 %, at the same time that implies a more sustainable production strategy with reduced carbon footprint and (2) simpler wastewater treatment strategies, with reduced stages, implies also reduced operational costs. So, in this last point, it is therefore necessary to find a compromise between the choice of technologies to improve the quality of the effluent and promote more circular recovery models, and the costs associated with the integration of these technologies.

Regarding the financial parameters scores (i.e. NPV, BCR and PP), it could be observed that the development of ACS-2 implies a positive NPV, thus meaning that the scenario under assessment is economically viable and feasible. On the contrary, ACS-1 is by far the less adequate, given its negative NPV, therefore, removing the BP unit does not seem

Table 6

Comparison between scenarios under an economic perspective.

Indicator	Unit	BCS	ACS	ACS-1	ACS-2	ACS-3
CAPEX	€	–	30,516,109	25,092,951	11,078,742	30,516,109
OPEX	k€/year	1166,512	3391,018	3153,680	2105,966	1948,080
REVENUE	€/year	3123,378	3372,595	3370,909	3225,231	3372,595
NPV	€	31,910,570	-29,841,662	-20,748,983	7,527,014	-6,311,702
BCR	ratio	1.68	-0.01	0.07	0.53	0.73
PP	year	–	-1656.46	115.51	9.90	21.42

like an adequate strategy to improve and enhance the economic performance, and this could also be observable by analyzing the BCR and PP scores obtained. With respect to ACS-2 and ACS-3, while for the BCR, ACS-3 is the best alternative, as it has a higher score, closer to 1, when analyzing the PP score, ACS-2 is, by far, the best choice, as less than 10 years are required to recover the initial capital expenditures.

As in the case of the economic profile, the development of the ACS does not imply an environmental improvement compared to the BCS, although certain similarities can be observed in some impact categories, such as in the case of MET and HCT, HNCT, with quite similar environmental impacts. In general, however, it can be said that the implementation of the ACS does not provide an improvement in the environmental sustainability potential, so a sensitivity analysis has also been developed within the environmental perspective. As can be seen in Fig. 4, the introduction of alternative sensitivity analyses implies environmental improvements compared to the ACS, leading to the proposal of a more sustainable wastewater valorization and treatment model. This is mainly observed for all the proposed sensitivity scenarios, but the one with the best results is the ACS-3, which is based on the use of a higher percentage of renewable energy. This sensitivity scenario manages to reduce the impact of ACS by an average of -18.80% , with the greatest reductions in environmental impact being achieved in the MET (-25.93%), HNCT (-25.44%), HCT (-21.67%) and TET (-2.15%) categories. On the contrary, some impact categories show no improvement in the reduction of environmental impact, although the values are not so significant, with an average increase of $+3.70\%$ compared to BCS. Specifically, the lowest improvement is observed for the TA impact category, with a value of $+5.19\%$ compared to BCS, while for GWP there is only a difference of $+0.89\%$. However, this scenario actually implies an improvement in the environmental impact compared to ACS, with an average reduction of 52.61% .

On the other hand, compared to the ACS, the ACS-2 reduces the environmental impact by an average of -29.54% , but compared to the BCS, it does not achieve any reduction values, but an increase in the

environmental impact that amounts to an average of 36.20% . Although it should be noted that the MET and HNCT impact categories are the ones that achieve similar values compared to BCS, with a difference in environmental impact that reaches $+13.99\%$ and 13.49% respectively.

In the case of ACS-1, the reduction in environmental impact is not as significant as in the case of ACS-2 compared to ACS, with an average of 6.81% , with the HNCT, MET and HCT categories showing the greatest reduction in impact compared to ACS, with -8.05% , -7.72% and -7.52% respectively.

Regarding the evaluation of the alternative scenarios to ACS in terms of circularity, the values obtained for the "flow indicators" and "circular action indicators" are more or less the same, with the exception of 8 scores, which are highlighted in red in Table 7. In the case of the "circular energy contribution" indicator, the alternative ACS-3, based on increasing the percentage of renewable energy in the process to obtain an analogous global warming value between ACS and BCS, implies that the score obtained is the same for the base case and the alternative proposal.

On the other hand, when evaluating the "Circular Material Productivity" indicator, since ACS-2 is committed to reducing the number of process steps in order to reduce the overall energy demand of the process, this results in a lower recovery of available high value-added products, which reduces the revenues dependency from linear consumption as in this scenario virgin NaCl is considered, although it is still higher compared to BCS. Energy reduction implies an improvement on the "energy demand" indicator, where the ACS-2 significantly reduces its value and comes closer to the BCS, which means that this scenario is not as energy demanded. However, the improvement of these values has its drawbacks, which can be observed in the categories of "reuse" and "regeneration", where ACS-2 obtains the lowest values, on the one hand because it is less able to generate economic gains per unit of treated water, and on the other hand due to the fact that ACS-2 achieves lower irrigation water quality values compared to ACS.

Therefore, it could be concluded that although the new alternative

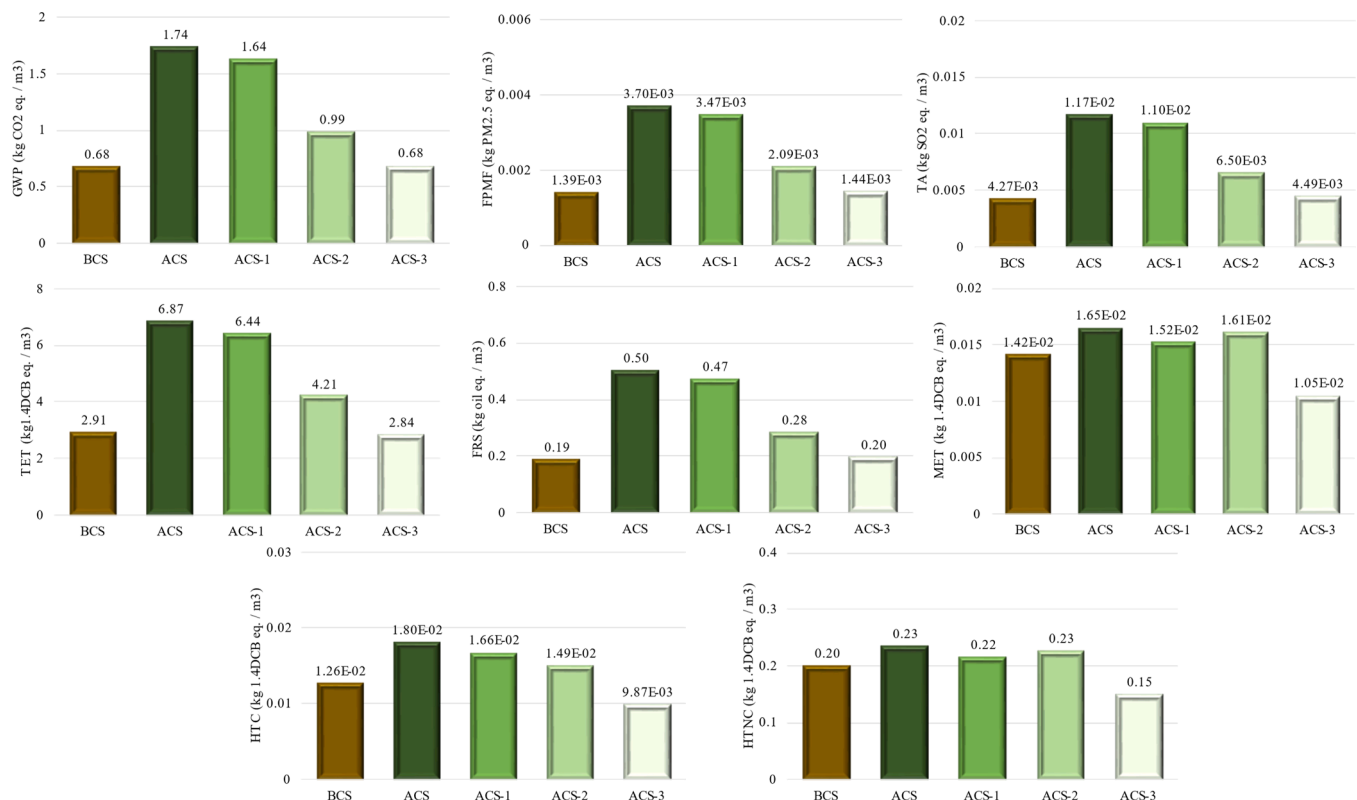


Fig. 4. Comparison between BCS, ACS and alternative ACS scenarios in terms of environmental scores following ReCiPe Midpoint methodology.

Table 7

Comparison between scenarios under a circularity perspective.

Resource flow indicators								
Category	Indicator		BCS	ACS	ACS-1	ACS-2	ACS-3	
Resource	Circular inflow (%)		–	99.98 %	100.00 %	100.00 %	99.98 %	
	Circular outflow (%)		–	81.93 %	81.93 %	84.82 %	81.93 %	
	Total circular flow (%)		–	90.95 %	90.96 %	92.41 %	90.95 %	
	Recovery efficiency (%)		–	81.91 %	81.93 %	84.82 %	81.91 %	
Energy	Renewable energy contribution (%)		40.00	14.29	16.67	33.33	40.00	
Economic	Circular material productivity (€/kg)		1.95	10.55	11.5	6.9	10.55	
Circular action indicators								
Category	Value	Indicator	BCS	ACS	ACS-1	ACS-2	ACS-3	
Process optimization	Added value	System productivity (kg/kg)	1.18	1.22	1.22	1.17	1.22	
		Energy demand (kWh/kg)	1.07	2.11	2.09	1.70	2.11	
		Chemical demand (kg/kg)	2·10 ^{−4}	1·10 ^{−4}	1·10 ^{−4}	5·10 ^{−5}	1·10 ^{−4}	
Repurposing	Value retention	Waste eco-efficiency (€/ton)	8683	15,962	16,819	9469	15,962	
Cascading	Value recovery	Nutrients recovery (kg/ton)	–	2.4	2.4	2.3	2.4	
		Minerals recovery (kg/ton)	0.2	0.2	0.1	0.2	0.2	
Regeneration	Regeneration of lost value	Irrigation water quality (mg/L)	[P]	1.52	0.10	0.10	0.09	0.10
			[Na]	566.12	84.58	84.58	86.56	84.58
			[Cl]	900.19	140.12	140.12	144.33	140.12
			[Mg]	85.02	5.65	5.65	5.11	5.65
			[Ca]	461.10	30.64	30.64	27.69	30.64
			[SO ₄]	535.11	35.56	35.56	32.14	35.56

models for ACS seem to show improvements in environmental and economic terms, they are not so noticeable in the case of the circularity assessment, where ACS-2 is shown as the least promising scenario. In order to improve and enhance the environmental and economic results, the efficiency and effectiveness in the use of electricity, as well as the choice of renewable energy sources instead of traditional ones, is a key aspect. In addition, the integration of an anaerobic digestion stage to utilize the carbon content of the sludge stream could be considered as a potential strategy to produce energy for the process itself, which could be used as an energy source in the more energy intensive stages of the process.

Sensitivity analysis was also conducted to assess the economic performance of the wastewater treatment process. Four alternative scenarios were evaluated: the base case scenario, where the economic value of treated wastewater was set to 0.5 €/m³; and a second scenario where the economic value was reduced to 0.4 €/m³ and increased to 0.6 €/m³. Additionally, a third scenario was developed to optimize resource and utility usage, thereby reducing operational costs (OPEX) by 15 %.

Furthermore, an operational sensitivity analysis was conducted to assess the impact of increasing the amount of recovered water on the systems. This increased water recovery would result in enhanced equipment efficiency, leading to a new case study where the amount of recovered water was increased by 10 %.

Table 8 provides the values obtained by developing the sensitivity assessments previously mentioned and described, based on economic and performance modifications (ACS, ACS-1, ACS-2, and ACS-3). This quantitative data is complemented by the bar chart offering a more granular view of their financial performance based on the BCR score. The selling price of treated water plays a pivotal role in determining the financial viability of all scenarios. At a lower price point (0.4 €/m³), none of the scenarios achieve a positive NPV or a BCR above 1, indicating that the revenue generated is insufficient to offset capital and operational costs. However, as the price increases to 0.6 €/m³, revenue improves significantly, reducing the financial gap and improving BCR values, although not always enough to reach profitability. This highlights the importance of market conditions in determining the feasibility of the proposed new wastewater treatment process.

The –15 % OPEX scenario demonstrates the substantial impact that operational efficiency can have on economic performance. Reducing OPEX directly improves the NPV and BCR across all scenarios. The improvement in BCR under this condition suggests that investments in energy efficiency, automation, or optimized maintenance could be strategic levers for enhancing project viability. Indeed, focusing on the

Table 8

Sensitivity analysis considering modifications on economic and performance indicators.

Item	0.4 €/m ³			
	ACS	ACS-1	ACS-2	ACS-3
CAPEX	30,516,109 €	25,092,951 €	11,078,742 €	30,516,109 €
OPEX	3391,018 €	3153,680 €	2105,966 €	1948,080 €
REVENUE	2972,482 €	2970,796 €	2825,118 €	2972,482 €
NPV	–36,366,296 €	–27,273,617 €	1002,381 €	–12,836,336 €
BCR	–0.12	–0.06	0.34	0.53
PP	–	–	15.41	29.79
Item	0.6 €/m ³			
	ACS	ACS-1	ACS-2	ACS-3
CAPEX	30,516,109 €	25,092,951 €	11,078,742 €	30,516,109 €
OPEX	3391,018 €	3153,680 €	2105,966 €	1948,080 €
REVENUE	3772,708 €	3771,022 €	3625,344 €	3772,708 €
NPV	–23,317,029 €	–14,224,349 €	14,051,648 €	212,932 €
BCR	0.11	0.20	0.72	0.94
PP	79.95	40.65	7.29	16.72
Item	–15 % OPEX			
	ACS	ACS-1	ACS-2	ACS-3
CAPEX	30,516,109 €	25,092,951 €	11,078,742 €	30,516,109 €
OPEX	2882,365 €	2680,628 €	1790,071 €	1655,868 €
REVENUE	3372,595 €	3370,909 €	3225,231 €	3372,595 €
NPV	–21,547,074 €	–13,034,935 €	12,678,305 €	–1546,608 €
BCR	0.17	0.26	0.80	1.04
PP	62.25	36.35	7.72	17.78
Item	+10 % Water recovery			
	ACS	ACS-1	ACS-2	ACS-3
CAPEX	30,516,109 €	25,092,951 €	11,078,742 €	30,516,109 €
OPEX	3391,018 €	3153,680 €	2105,966 €	1948,080 €
REVENUE	3504,871 €	3503,153 €	3357,483 €	3504,871 €
NPV	–27,684,643 €	–18,592,485 €	9683,637 €	–4154,682 €
BCR	0.03	0.11	0.59	0.80
PP	268.03	71.80	8.85	19.60

BCR, Fig. 5 shows that the scenario that performs better, namely the one providing the higher BCR is the one considering a reduction in the OPEX, followed by the increase on the treated water selling price. It also indicates that even high-CAPEX systems can become more attractive if operational costs are effectively managed. Similarly, the +10 % water recovery scenario contributes positively to the financial indicators by boosting revenue. While the effect is not as pronounced as the OPEX reduction, it still contributes to improving the BCR and reduce the payback period.

Based on the sensitivity analysis conducted across the three external

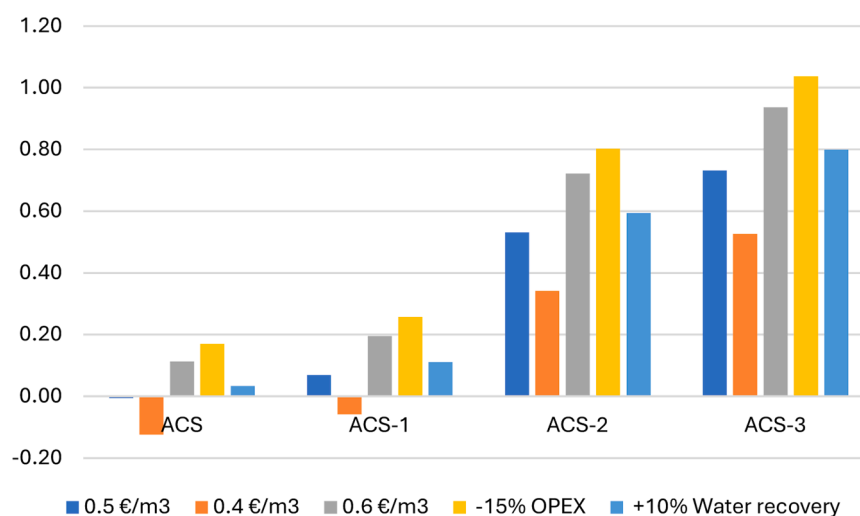


Fig. 5. Comparison between sensitivity scenarios considering the BCR score.

variables—selling price of water, -15% OPEX, and $+10\%$ water recovery—the scenario that consistently demonstrates the most favorable economic performance is the one of -15% OPEX. This condition yields the most significant improvements in NPV, BC), and Payback Period across all configurations, indicating that operational efficiency is a key driver of financial viability. While increasing the selling price of water also improves financial outcomes, this factor is often subject to external market forces and regulatory constraints, making it less controllable from a design or operational standpoint. Similarly, the $+10\%$ water recovery scenario contributes positively to revenue and performance metrics, but its impact is more modest compared to the OPEX reduction. Therefore, although all three variables enhance economic feasibility to varying degrees, the operational cost reduction stands out as the most effective and actionable strategy.

In conclusion, prioritizing strategies that reduce OPEX, such as energy efficiency measures, process optimization, should be the preferred path forward. These improvements not only enhance the economic sustainability of the system but also offer greater resilience across different market conditions.

3.6. Scenario assessment main analysis

With the aim of increasing the water cycle and promoting its reuse in the agricultural sector as irrigation water, the technological model presented in this article is considered suitable and adequate, since the concentration of pollutants in the treated water is significantly reduced. Thus, a high quality of water is obtained thanks to the integration of the system, which also allows the extraction and recovery of phosphorus and minerals, which can be used as an alternative to conventional products. Therefore, from a technological point of view and in terms of the quality of the treated water, the results obtained are more than promising. However, in the short and long term, efforts must be made to improve the energy efficiency of the system, since it is a very energy-intensive water treatment model, as well as to opt for increasing the use of renewable energy. On the other hand, also to work on the circularity of the system, the use of the dry sludge as a carbon source for energy production, in a cogeneration system, should also be explored as an alternative to improve the renewable energy contribution to the WWTP.

Additionally, an alternative approach involves expanding the boundaries of the ACS to include conventional processes used in the production of irrigation water, phosphorus, and minerals. These traditional methods—such as seawater reverse osmosis desalination, chemical phosphorus production, and mining—are characterized by linear flows (e.g., discharging effluents into the environment), high costs, and

significant environmental impacts. Therefore, expanding the boundaries of the ACS in the assessment could enhance the circular and sustainability benefits of the integration and provide a more comprehensive analysis.

3.7. Comparison with other studies

As previously mentioned, the primary novelty of the present article lies in its multidimensional analysis of an advanced wastewater treatment plant, encompassing environmental, economic, and circularity assessments. This comprehensive analysis is not as prevalent in the literature, as evidenced by Table 9, which was compiled based on a SCOPUS research conducted using the keywords “circularity AND life cycle assessment AND wastewater treatment.” Notably, the majority of articles focus on developing life cycle assessments (LCAs) or combining them with cost analyses (CAPEX and OPEX, but not LCC). Conversely, only a few articles concentrate on scoring circularity indicators, without considering a combined approach that evaluates all the pillars analyzed in this article.

4. Conclusion

This research paper presents a comprehensive methodology that integrates economic, environmental, and circular sustainability analyses to evaluate wastewater treatment technologies. The primary objective is to provide a holistic perspective on the potential of advanced treatment models to optimize resource recovery and reduce salinization. A key innovation of this research lies in the incorporation of additional process stages beyond conventional treatment, aimed at mitigating the environmental impact of high-salinity effluent streams while promoting circularity through the recovery of value-added compounds and stream recirculation.

The study compares a BCS with an alternative configuration that includes these advanced stages. Results from the combined assessment reveal that while the ACS significantly enhances circularity and resource recovery, it also introduces higher energy demands due to the added process units. This leads to increased environmental impacts and elevated CAPEX and OPEX, complicating the demonstration of economic viability and negatively affecting the NPV.

This trade-off highlights a central challenge: the transition from linear to circular wastewater treatment models must balance sustainability goals with economic and technological feasibility. To address this, the research emphasizes the need for optimization strategies focused on improving equipment efficiency, maximizing resource recovery, and accounting for the economic benefits of avoided

Table 9

Comparison with other studies. Acronyms: LCA – Life Cycle Assessment, LCC – Life Cycle Cost, SWOT - Strengths, Weaknesses, Opportunities, and Threats.

Reference	Brief description	Does the study include...			Some comments and comparisons
		LCA?	LCC?	Circularity indicators?	
Aleisa et al. 2022	Inclusion of wastewater tertiary treatment including ultrafiltration (UF) and reverse osmosis (RO)	Yes	No, only costs analysis	No	This article of Aleisa et al. (2022) is based on analyzing the differences among the proposed UF+RO and UV disinfection and conventional seawater desalination, but a LCC is not developed, so economic feasibility is not included, neither an analysis of circularity using performance indicators, both analyses done in this article. Regarding the LCA, the functional unit considered is not the same, the impact loads could not be compared
Karkou et al. 2024	Three scenarios for tertiary treatment considering the combination of seven technologies: equalization, coagulation/flocculation, sedimentation, sand/biological /activated carbon filtration and UV disinfection	Yes	No, only costs analysis	No	The total costs of the scenario implying higher recovery and the higher quality of the treated water are the highest ones (8.54€/h vs 0.003 €/h of operational costs), which is in line with the outputs of this article. Regarding the LCA, the impact loads are normalized to mPt and environmental footprint method is used, so it could not be compared.
Lena et al. (2025)	A multiple-criteria decision analysis compared three scenarios based on ultrafiltration, co- and slow-forming dynamic membrane bioreactor for wastewater treatment and resources recovery	Yes	No, only cost analysis	No, only flow composition analysis	The environmental impacts are not analyzed per impact category, only in terms of cumulative environmental impacts in mPts, thus not being able to compare with the present study. But the integration of more process units reduces the environmental loads in this case study, with electricity not having almost impact, but yes, the emissions to water. So, it could be concluded that the equality of the water is not as high as the one providing in this study, that could be the reason of the higher environmental loads. Regarding the economic viability, the study by Lena et al. (2025) has not analyze it, only CAPEX and OPEX, so it is not comparable. On the other hand, circularity is not assessed, only treatment performance, based on the analysis of the wastewater components flows.
Bhambhani et al. 2023	Development of an improved circularity indicator by refining the restoration, regeneration and linear flows terms. Use of the indicator in a case study using treated water for irrigation.	No	No	Yes, material circularity indicator	A modified material circularity indicator is developed, focused also on biogeochemical flows (as groundwater infiltration and nitrogen emissions). In this case the water from the wastewater treatment plant is used for irrigation on agricultural land, similarly, as done in this article, but the system boundaries are only focused on the agricultural land stage, so it could not be compared to the present article.
Berger and Thiede, 2023	Analysis of how the recycling of water affects over the water depletion and global warming potential.	Yes	No	No	The main outcomes highlight that as much water recycled, as lower the environmental loads. This is in line with the outcomes of this article, as the LCA results shows better performance when opting for increasing the resources recovery and water recycling potential
Ruff-Salís et al. 2022	Integrating additional technologies in a wastewater treatment plant for nutrient recovery and biogas production.	Yes	No	No	Biogas production alone doesn't offset the environmental cost of infrastructure, though autotrophic nitrogen removal improves effluent quality. Recovering both phosphorus and energy helps reduce environmental loads, thus meaning that higher technological implementation implies a reduction on pollution potential. This is in line with the outcomes of this article, as LCA shows better performance from an environmental sustainability perspective when increasing water quality with extra process units.
Buonocore et al. 2018	Environmental analysis of five wastewater and sludge management scenarios from conventional disposal to increasingly circular strategies involving biogas production, sludge gasification, fertirrigation, and renewable energy integration.	Yes	No	No	The study reveals that increasing circularity in wastewater treatment can lead to notable environmental benefits. This outcome is in line with the results achieved by the present article. Regarding LCA, scenarios involving biogas production and sludge gasification show reductions in GWP and FRS, thanks to energy recovery and reduced reliance on fossil fuels. Even in the present article energy recovery is not developed, the use of renewable energy has been considered as sensitivity analysis, which reduce the reliance on fossil fuels and, also, implies reduced environmental loads, as happened in the article of Buonocore et al., 2018.
Rodrigues et al. 2024	Five wastewater treatment models considering different technologies for resources recovery and four wastewater treatment plants under analysis	No	No	Yes, SWOT analysis	Various KPIs have been analyzed, considering materials, water, energy and economic categories, some of them the same as the ones assessed in this article. Concretely the following Circular inflow 40 %, which is significantly lower than the present article (99–100 %) Circular flow 25 %–59 %, which is significantly lower than the present article (90–92 %) Material productivity 636 €/kg, which is significantly higher than the present article (6.9–11.5 €/kg) Renewable energy use 5 %–42 %, which is in line with the present article (14 %–40 %)

environmental impacts.

Sensitivity analyses identify key environmental hotspots, with the increased use of renewable energy emerging as the most effective strategy for reducing the environmental footprint. Furthermore, the study underscores the importance of political support and stakeholder engagement, including financial incentives and subsidies, to foster the development and integration of innovative treatment technologies.

Regarding the posed RQs in the introduction section, the following outcomes were achieved:

RQ1: How does the integration of advanced treatment technologies influence circularity performance? The integration of advanced treatment technologies enhances circularity by enabling the recovery of a broader range of resources and components, thereby improving the overall performance of WWTPs in circular systems. In fact, the recovery efficiency has been increased to almost 85 %, while the circular material productivity from 1.95 €/kg, characteristic of the base case scenario, to 11.5 €/kg in the case of the alternative one based on more resource recovery.

RQ2: What are the environmental trade-offs associated with the increase of energy composition in circular-oriented WWTP processes? The case study demonstrates that while advanced technologies improve resource recovery, they also introduce significant energy demands—particularly in filtration stages—which result in increased maintenance and environmental burdens. Concretely, from the 1.07 kWh/kg required by the base case scenario, the proposed new technological development implies the requirement of 2.11 kWh/kg, which is almost the double amount of energy required.

RQ3: To what extent do advanced treatment technologies demonstrate economic feasibility? Economic feasibility remains a challenge; although additional units recover valuable products, the high costs of advanced technologies hinder viability unless those products are appropriately valued within the system.

RQ4: How can standardized circularity frameworks, such as ISO 59,004, help assess the multidimensional impacts of WWTPs in transitioning to cascading production systems? Frameworks like ISO 59,004 provide a foundational structure for identifying and measuring key circularity indicators. However, further methodological development is needed to integrate sustainability dimensions and support comprehensive decision-making.

Ultimately, the findings position wastewater treatment plants as potential cascading production models and resource hubs. They serve as a foundation for future research aimed at enhancing treatment efficiency, reducing environmental burdens, and improving economic performance—paving the way for scalable, sustainable, and circular water management solutions.

CRediT authorship contribution statement

Ana Arias: Writing – original draft, Formal analysis, Conceptualization. **J.M. Ribeiro:** Investigation, Formal analysis, Data curation, Conceptualization. **G. Tsalidis:** Writing – review & editing, Formal analysis. **D. Renfrew:** Writing – review & editing, Formal analysis. **D. Dias:** Writing – review & editing, Conceptualization. **Maria Avramidi:** Formal analysis, Data curation. **Maria Kyriazi:** Formal analysis, Data curation. **Maria Teresa Moreira:** Writing – review & editing, Supervision. **E. Katsou:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

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

The authors are grateful to the European Commission for supporting the activities carried out in the framework of the WATER-MINING (project under grant agreement No. 869474). The authors especially thank Maria Avramidi, Maria Kyriazi, Constantinos Loizou, and Wokke Wijdeveld from the WATER-MINING project for operating the pilot system. The opinions expressed in this document reflect only the views of the authors and do not reflect the European Commission's opinions. The European Commission is not responsible for any use that may be made of the information it contains. A. Arias also thanks the Galician Government for financial support (Grant reference ED481B-2023-072). A. Arias, S. and M.T. Moreira, authors belong to the Galician Competitive Research Group (GRC ED431C 2021/37) and to the Cross-disciplinary Research in Environmental Technologies (CRETUS Research Center, ED431G 2023/12).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.watres.2025.124406](https://doi.org/10.1016/j.watres.2025.124406).

Data availability

Data will be made available on request.

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