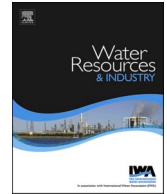




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Sustainability in the treatment of wastewater from canning industry effluents

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ABSTRACT

The treatment of wastewater from the fish canning industry presents specific challenges due to its high organic load and elevated salt and nutrient concentrations. This study combines modelling and real-world data from an operating industrial plant to evaluate the performance and environmental impact of a wastewater treatment plant located in Galicia, Spain, which treats effluent from a tuna canning factory. The treatment setup includes physical pretreatment, dissolved air flotation, sequential biological reactor, and sludge treatment units. Based on the simulation results, a Life Cycle Assessment (LCA) was applied using the ReCiPe Midpoint (H) methodology, considering eight environmental impact categories. The results indicate that the greatest impact corresponds to the power consumption of the sequencing batch reactor for aeration, which results into 6.75 kg CO₂-eq./m³. The sensitivity analysis, which included different European electrical profiles and the replacement of the coagulant polyaluminium chloride with ferric chloride, identified significant opportunities for environmental improvement. In this regard, the climate change category may reach reductions up to 4.45 and 0.38 kg CO₂-eq./m³, for energy and chemical substitutions respectively. This integrated approach demonstrates the potential of combining simulation and LCA as a decision-support tool to improve sustainability in industrial wastewater treatment in the canning sector.

Acronym list

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CC	Climate Change
DAF	Dissolved Air Flotation
DEA	Data Envelopment Analysis
DS	Dry solids
F _{BS}	Readily Biodegradable Organic Matter Fraction Parameter
F _{NA}	Ammonium Fraction Parameter
FRS	Fossil Resource Scarcity
F _{PO4}	Phosphorus Fraction Parameter
F _{UP}	Particulate Non-Biodegradable Organic Matter Fraction Parameter

(continued on next page)

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F _{XSP}	Slowly Biodegradable Organic Matter Fraction Parameter
FWE	Freshwater Eutrophication
GHG	Greenhouse Gas Emissions
GS	Grease Separation
HT	Homogenization Tank
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISS	Suspended Inorganic Solids
IR	Ionizing Radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCF	Methane Correction Factor
ME	Marine Eutrophication
MRS	Mineral Resources Scarcity
ODP	Ozone Depletion Potential
RMSE	Root Mean Square Error
RD	Rotary Screen
SBR	Sequencing Batch Reactor
PAC	Polyaluminum Chloride
PIC	Proportional-Integral Controller
TSS	Total Suspended Solids
TN	Total Nitrogen
TP	Total Phosphorus
UASB	Upflow Anaerobic Sludge Blanket
WC	Water Consumption
WWTP	Wastewater Treatment Plant

1. Introduction

In Europe, the industrial sector is the largest consumer of water resources, accounting for about 49% of total freshwater withdrawals, which is significantly higher than domestic consumption (21%) [1]. Industrial wastewater is generated after water use across diverse sectors, including petrochemicals, pharmaceuticals, pulp and paper, textiles, iron and steel, and the food industry, and is typically characterized by high pollutant loads and heterogeneous compositions, often including toxic compounds [2]. Within the food industry, fish processing can be characterized by effluents exhibiting Chemical Oxygen Demand (COD) concentrations between 3700 and 5000 mg/L and containing fats, salts, and suspended solids, which pose major challenges for environmental management and effective treatment [3–5]. This is especially relevant due to the increasing wastewater generation from the growth of the industry. Spain, for example, has developed a robust sector, particularly in smoked, processed, and canned products. Tuna preserves dominate the national output, representing about 70% of EU tuna canning production, with the Galician region accounting for more than 85% of Spain's share [6].

Fish canning involves multiple processing steps, including preparation, cooking, packaging, sterilization, and final conditioning that generate complex and highly variable effluent streams [7]. Daily and seasonal fluctuations complicate accurate wastewater characterization, with peak organic loads often occurring during morning cooking operations and higher suspended solids during nighttime cleaning [8]. These fluctuations, together with the intermittent operation of treatment systems, hinder the stability of conventional wastewater treatment. Primary treatment in fish canning facilities typically includes sedimentation, pH adjustment, and dissolved air flotation (DAF), while secondary treatment relies on aerobic or anaerobic biological processes. Aerobic technologies such as activated sludge, sequencing batch reactors (SBR), and trickling filters are widely used for COD and nutrient removal. Anaerobic systems, including Upflow Anaerobic Sludge Blanket (UASB) reactors, anaerobic filters, and fluidized bed reactors, can achieve COD removal rates of up to 90% while generating biogas as a by-product. Nevertheless, these conventional approaches often entail high energy consumption, mainly associated with aeration, chemical use, and sludge management, making sustainability a critical issue [9, 10].

Wastewater treatment facilities are not only water-intensive but also energy-demanding. Globally, it is estimated that they account for 3%–5% of total electricity uses and contribute 1%–5% of national greenhouse gas (GHG) emissions, primarily in the form of methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂), produced both directly by biological processes and indirectly through energy consumption [11]. For this reason, there is an urgent need for solutions that enhance treatment efficiency of existing wastewater treatment plants (WWTPs) while reducing energy demand and environmental impacts.

Therefore, process simulation has emerged as a tool to address technical challenges, including also energy and water demand optimization. When operational data are limited or variable, simulation enables detailed modelling of physical, chemical, and biological processes, providing site-specific and dynamic inventories [12]. There is different specific software to facilitate modelling of wastewater treatment processes including BioWin™, GPS-X, SUMO, WEST, SIMBA, STOAT, AQUASIM and Matlab. BioWin™ is a widely used tool for the comprehensive design and optimization of WWTPs, particularly due to its capabilities in chemical process

modelling and sludge treatment, as well as for its robustness and extensive use in engineering practice [13]. Moreover, Biowin™ has been used mostly for the simulation of urban wastewater treatment processes, including aerobic and anaerobic biological technologies, as well as for resource recovery [14–17]. Exceptions include the studies by Balakrishnan et al. [18]), Ravi et al. [19] and Elawwad et al. [20], who used the program for industrial tannery, dairy and coke-oven wastewaters. Despite its advantages, BioWin™ presents several limitations since it relies on fixed model structures and predefined assumptions, which limit the user's ability to modify kinetic expressions, gas–liquid mass transfer formulations, or microbial process pathways [21]. In particular, greenhouse gas emissions in BioWin™ are typically estimated to be using simplified or semi-empirical approaches, which may not fully capture micro-scale heterogeneity or short-term operational variability [21]. Moreover, the accuracy of results heavily depends on the quality of initial data. Therefore, BioWin™ often requires model modifications for accurate calibration [22]. Also, it may not predict with accuracy the chemical characteristics of the system under study [23].

Even a technologically optimized process does not guarantee sustainability, which is why process modelling should be integrated with environmental assessment tools. In this regard, informed decision-making for environmentally sustainable wastewater management can be done considering the combination of the Life Cycle Assessment (LCA) methodology with data gathered from BioWin™ modeler. This software has already been combined with LCA [24–27] for other sectors but it has not been used to assess fishing and cannery wastewater. The research has focused primarily on municipal systems or facilities with anaerobic digestion, energy recovery, or resource separation. Also, aerobic industrial systems with complex and saline effluents have received less attention.

Furthermore, the BioWin™ model employed in this study functions as a dynamic digital twin of the wastewater treatment system. Although it currently relies on historical operational data and average data scenario simulations rather than real-time sensor inputs, it captures the behavior of the system, predicts responses to operational changes, and can be readily adapted to incorporate live data in future implementations. According to recent literature, digital twins exist on a spectrum from static models to fully real-time systems; our model fits within this intermediate category, providing predictive capabilities consistent with the digital twin concept [28].

Within this context, the aim of this research was to evaluate the environmental performance of a fish canning wastewater treatment plant considering LCA methodology. Primary data has been initially gathered from a full-scale Galician WWTP to be then dynamically modeled with Biowin™ in order to be able to optimize the system. Fluctuations in the chemical and microbiological composition of wastewater from the incorporation of perturbations (e.g., coagulant dosing) have also been considered. In this regard, Biowin™ was used for the creation of a digital twin of the facility that enabled the development of alternative scenarios.

2. Methods and methodology

2.1. Scenario description

2.1.1. Water line

The WWTP under study is located in Galicia, the northwest region of Spain, and presents the configuration shown in the process flow diagram of Fig. 1. The most relevant treatment units across both water and sludge lines are depicted in this figure. The plant is structured into four main stages: pretreatment (T.1), primary treatment (T.2), secondary treatment (T.3), and sludge line (T.4).

The processing cannery effluent is first fed to a rotary screen for coarse solids removal, followed by a 100 m³ homogenization tank equipped with an aeration system (A1) and two transfer pumps (B1 and B2). The flow then enters into a 1 m³ grease separator fitted with a blower (R1) and scraper (S1) for removing fats and oils, which are later collected and externally managed for valorization as

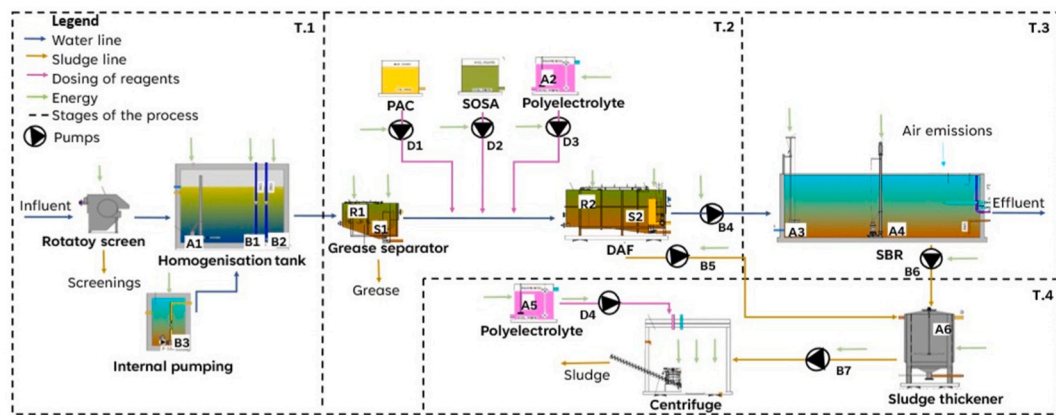


Fig. 1. Flow diagram of the cannery wastewater treatment plant under research. A1: Homogenization tank aerator; A2: Polyelectrolyte agitator; A3: SBR agitator; A4: SBR aerator; A5: Polyelectrolyte agitator; A6: Thickener agitator; B1: Pumping 1 Homogenization; B2: Pumping 2 Homogenization; B3: Internal pumping; B5: DAF sludge pump; B4: DAF outlet pump; B6: SBR sludge pump; B7: Sludge pump to centrifuge; D1: PAC dosing unit; D2: sodium hydroxide dosing unit; D3: Polyelectrolyte dosing unit; D4: Polyelectrolyte dosing unit; R1: Degreaser blower; R2: DAF blower; R3: Centrifuge scraper; S1: Degreaser scraper; S2: Dissolved air flotation (DAF) scraper; NaOH: Sodium hydroxide SBR: Sequencing Batch Reactor; PAC: Polyaluminum chloride.

industrial by products. From the grease separator, the effluent enters a DAF unit with a capacity of 3.75 m³, equipped with a blower (R2) and a sludge scraper (S2). At this stage, pH is adjusted automatically through the dosing of a 50% sodium hydroxide (NaOH) solution. Polyaluminum chloride (PAC) is added as a coagulant, along with a flocculant solution prepared manually in a continuously stirred tank (A2). The flocculant remains active as long as the level sensor detects a sufficient volume of solution inside the tank. The clarified effluent is then directed to a SBR with a total volume of 300 m³, operating in three 8-h cycles comprising four phases: filling and biological reaction for nitrification and denitrification (6 h); sedimentation (2 h); discharge of the supernatant to the sewer network via a Proportional-Integral Controller (PIC) valve (39 min) and brief closure of the PIC valve (2.5 min).

The discharge limits for this plant are (<1000 mg COD/L; <500 mg BOD/L; <500 mg TSS/L; <40 mg TP/L; <40 mg TN/L). When needed, anti-foaming agents or complementary chemicals such as Magnasol (a PAC-based solution) are dosed into the SBR using a metering pump that operates at predetermined intervals triggered by foam detection.

2.1.2. Wastewater characteristics

The tuna canning industry exhibits variable wastewater flow rates (37 - 93 m³/d), caused by the seasonality of the production patterns. The composition changes between 2000 and 11,000 mg COD/L and 250 to 2300 mg TSS (total suspended solids)/L, which is a higher concentration of organic and inorganic matter than typical urban WWTPs [26]. The COD/BOD₅ ratio is between 1.7 and 2.8, indicating the presence of both biodegradable and more recalcitrant organic compounds. According to Anh et al. [27], a BOD₅/COD ratio close to 0.4 is associated with high biodegradability, while values between 0.2 and 0.4 reflect low biodegradability. In this regard, the results obtained are at the upper limit of the low biodegradability range, suggesting an effluent with a partially degradable organic fraction, typical of industrial discharges from the food sector. High concentrations of Total Nitrogen (TN), (150 - 700 mg/L) and Total Phosphorus (TP) (26 - 90 mg/L) are also present, along with fats and oils (77 and 1150 mg/L), which can adversely affect the performance of biological treatment processes if not properly removed. Finally, the pH fluctuates from 5.4 to 7.5 due to the use of chemicals during cleaning operations and the timing of different production activities.

2.1.3. Sludge line

The primary sludge is generated by the DAF unit, which is pumped using the DAF sludge pump (B5). Additionally, secondary excess sludge from the SBR is transferred via the SBR sludge pump (B6). Both sludge streams are then stored in a gravity thickener, a stainless-steel tank equipped with an agitator (A6) and a safety overflow.

In case of overflow, the excess sludge is redirected back to the homogenization tank via the overflow channel. The thickened sludge is then pumped to a centrifuge using a sludge feed pump (B7) for dewatering. The centrifuge is assisted by a scraper (R3) and a screw conveyor and is dosed with a controlled amount of flocculant to enhance the dewatering process. The resulting dewatered sludge is transported to an external specialized company, where it is primarily used as feedstock for composting.

2.2. Modeling with BioWin

A digital twin was developed using BioWin™ v6.3, a comprehensive simulation software that integrates hydraulic, chemical, and biological models. It enables the prediction of fluctuations in the chemical and microbiological composition of wastewater [28]. BioWin™ offers two simulation modes—steady-state and dynamic—with the dynamic mode selected for this study. Although averaged primary, supplemented with bibliographic, data was used, this mode of operation of the software was chosen to consider the inherently time-dependent reaction processes, the timely operation of equipment (i.e., loading, mixture and discharge in the SBR), simulation of

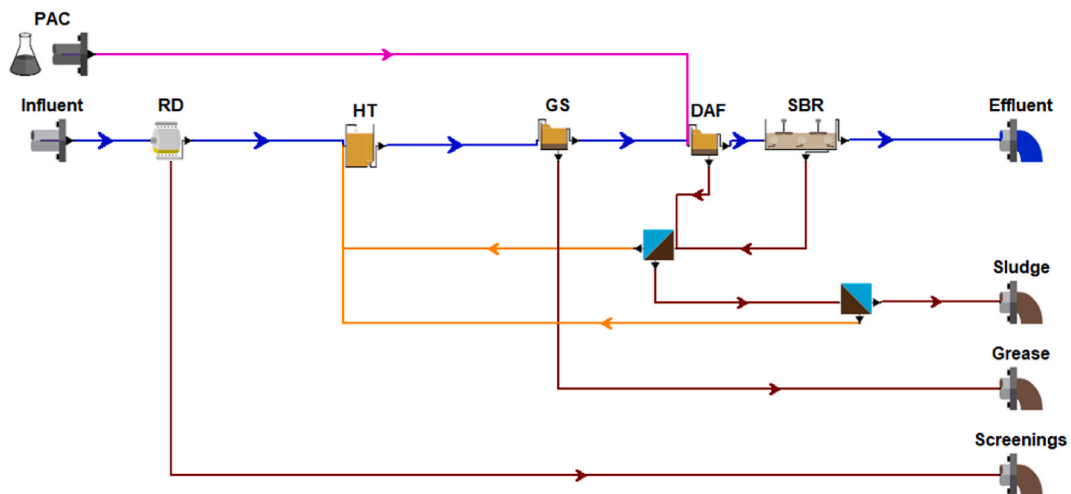


Fig. 2. Process flow diagram of the process implemented in BioWin™. DAF: Dissolved air flotation; HT: Homogenization tank; GS: Grease separator; PAC: Poly-aluminum chloride; RD: Rotary Screen; SBR: Sequencing Batch Reactor Biological reactor.

variation of parameters, alignment with future digital twin implementation with live data.

The developed model (Fig. 2) was configured to replicate the operating conditions of the treatment plant using historical operational data collected between January and November 2023. These data correspond to real plant measurements; however, they were processed and averaged to define representative operating conditions for the simulation period. The dynamic simulation was run for a total period of 80 simulated days to ensure biomass stabilization and to eliminate the influence of initial transient conditions. The results reported correspond to the stabilized operational phase of the model. Data from December was excluded due to a temporary shutdown of the tuna canning facility, which also suspended WWTP operations. A representative average flow rate of 54.6 m³/d was used, reflecting typical operating conditions during the observed period. Influent characterization was performed using BioWin™ *Influent Specifier* tool, which converts typical wastewater quality parameters (e.g., COD, BOD₅, TSS, TN, TP) into a set of biochemical fractions. The average influent concentrations were 5045 mg COD/L, 1790 mg BOD₅/L, 1535 mg TSS/L, 356 mg TN/L, 54 mg TP/L (Table 2 for more process information). BioWin™ applies internal rules and predefined equations to calculate fractions such as soluble biodegradable, slowly biodegradable particulate, and non-biodegradable particulate [29,30].

The treatment process incorporates a rotary screen, modeled in BioWin™ as a *Micro-Screen* unit, which facilitates the physical removal of coarse solids. This unit was configured with 85% total solids capture efficiency and an additional 15% retention of inert volatile particulate solids. These values fall within the range typically reported for industrial microscreens, which can vary from 10% to 90% depending on mesh size and influent characteristics [31]. BioWin™ specifies that this unit has no hydraulic volume or storage capacity, meaning removal is applied instantaneously to the defined fractions [30]. The energy consumption was set at 2.75 kWh, based on operational data (Table 1). The values in Table 1 correspond to actual electricity demand (kWh) and were derived from the nominal power of each device, the number of installed units, and their average daily operating hours. Since this information is crucial for assessing sustainability, the detailed breakdown is provided in the Supplementary Material (Table S2).

The pretreated flow enters a homogenization tank, represented in BioWin™ as an *equalization tank*. This tank has a depth and width of 2.0 m, with an agitation power of 1.48 kWh/m³, matching the energy consumption of the actual equipment. The flow then proceeds to a grease separator, modeled as a *grit trap*, with a depth and width of 0.1 m, and 80% efficiency for the removal of suspended inorganic solids (ISS). Its energy consumption is set at 0.04 kWh/m³.

Following this, physical treatment continues in a DAF system, also modeled as a *grit trap* with the same dimensions. This unit was configured with 90% ISS removal efficiency, based on values typically reported for industrial DAF systems [32]. Mechanical power input was set at 0.43 kWh/m³. In addition, PAC is dosed as a coagulant at a rate of 13.76 L/d.

The clarified effluent is then pumped to a SBR, simulated in BioWin™ using the *SBR Tank Individual* unit, with a depth of 6 m and a width of 7 m. The biological reaction phase is modeled with an intermittent aeration program to simulate alternating aerobic and anoxic conditions. Dissolved oxygen (DO) concentration is controlled using a time-based setpoint: 1 h without aeration (0 mg DO/L) followed by 1 h of aeration (3.0 mg DO/L), repeated throughout the 6-h reaction phase. These setpoints and durations were based on real operating values from the treatment plant.

Sedimentation begins when the tank is 92% full, with an initial liquid volume set at 80%. Each operational cycle lasts 8 h, including a 2-h settling phase and a 39-min effluent discharge phase, all conducted at a constant temperature of 20 °C. The sludge wasting rate was set at 5 m³/d, which corresponds to the volumetric withdrawal of mixed liquor. After thickening and dewatering, the sludge production amounts to approximately 1720 kg DS (dry solids)/d.

In the sludge line, excess sludge from the SBR is first sent to a thickening unit, represented in BioWin™ as a dewatering unit with an energy consumption of 3.53 kWh/m³. The thickened sludge is then processed in a second dewatering unit, simulating a centrifuge, configured with 70% dewatering efficiency and a specific energy consumption of 0.24 kWh/m³.

The accuracy of the model, as described above, was verified by calculating the root mean square error (RMSE) between the simulated concentrations and the actual effluent data. The model showed an overall RMSE of 2.49 mg/L, indicating an excellent level of fit. Detailed results are presented in Table S3 in the Supplementary Material. Also, Table S4 summarizes the BioWin™ default fractions, the calibrated values used in this study, and the absolute difference between them. The main deviations were observed in the

Table 1

Data used by BioWin™ software. BOD: Biochemical Oxygen Demand; COD: Chemical Oxygen Demand; DAF: Dissolved air flotation; SBR: Biological reactor; TN: Total nitrogen; TP: Total phosphorus; TSS: Total Suspended Solids.

Treatment unit	Rotatory screen	Homogenization tank	Degreaser	DAF	SBR
Function	Coarse Solids Removal	Flow and load equalization	Separation of greases	Solid-liquid separation by flotation (with coagulation)	Sequential biological treatment
Dimensions	-	2 m × 2 m	0.1 m × 0.1 m	0.1 m × 0.1 m	6 m × 7 m
Volume (m ³)	-	100	1	3.75	300
Removal efficiency COD (%)	20	0	25	80	90
Removal efficiency TSS (%)	30	0	35	90	95
Removal efficiency TN (%)	5	0	10	35	75
Removal efficiency TP (%)	5	0	10	40	70
Energy consumption (kWh/m ³)	0.05	1.48	0.04	0.43	3.53

Table 2

Life cycle inventory, expressed per 1 m³ of treated wastewater). BOD: Biochemical Oxygen Demand; CH₄: Methane; COD: Chemical Oxygen Demand; N₂O: Nitrous Oxide; TN: Total nitrogen; TSS: Total Suspended Solids; TP: Total phosphorus.

Life cycle inventory	Units	Pre-treatment	Primary treatment	Secondary treatment	Sludge line
Inputs from Technosphere					
<i>Materials</i>					
COD	kg	5.05	-	-	-
TN	kg	0.36	-	-	-
TP	g	54.00	-	-	-
TSS	kg	1.53	-	-	-
BOD	kg	1.79	-	-	-
Poly-aluminum chloride	g	70.00	-	-	-
Polyelectrolyte	g	4.40	-	-	0.38
Sodium hydroxide	g	30.00	-	-	-
Antifoam	g	40.00	-	-	-
Magnasol	g	10.00	-	-	-
<i>Energy</i>					
Medium voltage electricity	kWh	1.71	0.52	3.53	0.89
Outputs to Technosphere					
<i>Products</i>					
Sludge	kg	-	-	-	31.13
Grease	kg	-	-	-	0.73
Screenings	kg	-	-	-	449.45
Outputs to the Environment					
<i>Emissions to air</i>					
N ₂ O	g	-	-	2.10	-
CH ₄	g	-	-	6.22	-
CO ₂	g	-	-	32.00	-
<i>Emissions to water</i>					
COD	kg	-	-	0.11	-
TN	g	-	-	38.93	-
TP	g	-	-	6.90	-
TSS	kg	-	-	0.11	-
BOD	g	-	-	38.93	-

fractions F_{BS} (readily biodegradable organic matter), F_{XSP} (slowly biodegradable organic matter), F_{UP} (particulate nonbiodegradable organic matter), and F_{NA} (ammonium), reflecting the predominance of particulate organic matter, proteins, and fats in the influent. The soluble F_{NA} and phosphorus (F_{P04}) fractions had lower values than the reference values, indicating that most of these nutrients are associated with particulate organic matter.

2.3. Life Cycle Assessment

The LCA methodology was applied to evaluate the environmental impact of the WWTP, identifying critical inputs (those with the greatest influence, also known as *hotspots*) and proposing operational improvements through sensitivity analyses. The study was conducted in accordance with the guidelines set out in ISO 14040/44:2006 [33,34]. The goal is to support informed decision-making that promotes sustainability and minimizes the environmental footprint throughout the operational life of the cannery wastewater treatment plant.

2.3.1. Definition of system boundaries and functional unit

The analysis was conducted using a technological cradle-to-gate system boundary, covering all direct and indirect emissions from the point at which industrial wastewater enters the facility to the treated water outlet. Upstream impacts of the wastewater itself were considered burden-free, while the environmental effects of chemicals and energy used during treatment were accounted for. Although the water treatment life cycle was addressed, the handling, disposal, or valorization of sludge (e.g. thermal drying, transport, agricultural recovery), greases, and screenings fell outside the system boundaries. A cut-off system model with allocation by ranking was applied, and the construction, maintenance, and dismantling phases were beyond the study scope.

Although the facility was designed to comply with industrial discharge limits (Table S1), which are substantially less stringent than those established in the Urban Wastewater Treatment Directive (EU) 2024/3019, a baseline scenario assumed direct discharge of the effluent to the aquatic environment. In practice, however, and in strict compliance with legislation, the effluent is further treated at the local urban WWTP, where it is mixed with domestic and other industrial wastewaters. This system boundary assumption in the LCA was adopted to ensure that changes in the BioWin™ model configuration (e.g., coagulant substitution) resulted in noticeable differences in the environmental impact profile. This choice also reflects the difficulty of assessing how modifications in the canning industry's wastewater treatment would propagate through downstream processes designed for the joint treatment of urban wastewater streams. Explicit modeling of the downstream WWTP would require detailed data on plant configuration, removal efficiencies, and the representativeness of the facility's flow relative to other wastewater sources, which lie beyond the scope of this study. To avoid misinterpretation of absolute results, additional calculations were performed assuming that the effluent was not discharged to the

aquatic environment. However, in this case, potential changes to the BioWin™ model were not considered in the evaluation.

There were no limitations in the temporary system boundaries caused by the use of literature data to complete the inventories, although the foreground primary data was dated in 2023 (as indicated in Section 2.2). Ecoinvent® v3.8 database was used as the basis for background inventory data. When it comes to geographical system boundaries, cannery wastewater treatment was studied within a Spanish/European context.

The defined functional unit is 1 m³ of treated wastewater, as typically applied in environmental assessment studies of the sector [35–38]. This scope is consistent with the objective of the study, which is aimed at evaluating the environmental performance of the operational phase of a real industrial plant and identifying improvement opportunities related to energy consumption and chemical use. Thus, the analysis focuses on the flows and emissions directly linked to the daily operation of the system, providing a solid basis for environmental optimization of the process.

2.3.2. Life cycle inventory

The life cycle inventory for the wastewater treatment system was developed using a bottom-up approach, primarily based on operational data provided by the WWTP operator. This includes chemical and energy consumption, and sludge production, all normalized to the functional unit of 1 m³ of treated wastewater (Table 2). On the other hand, a detailed description and justification of the selected Ecoinvent® datasets used to model chemical and energy inputs are provided in the Supplementary Material (Section S1 and Table S5).

Atmospheric emissions generated in the SBR biological reactor (N₂O and CH₄) were estimated using emission factors recommended by the Intergovernmental Panel on Climate Change (IPCC) for industrial wastewater treatment. In the case of nitrous oxide (N₂O), a factor of 0.039 kg N₂O–N/kg N treated was applied, while methane (CH₄) emissions were calculated using the corresponding Methane Correction Factor (MCF) of 0.1 multiplied by the maximum methane producing capacity of 0.25 kg CH₄/kg COD [38]. It should be noted that the CH₄ emissions originated in the SBR did not come from the biological normal activity of the microorganisms but the objective was to highlight the existence of other micro-scale and operational realities such as stripping of dissolved methane present in the influent, release from anaerobic micro-zones within sludge flocs, or methane formed during non-aerated phases (i.e., filling and settling) [39–41]. It should be noted that BioWin™ estimates direct CO₂ emissions (shown in Table 2 for secondary treatment) generated by the treatment system as part of its advanced simulation capabilities. It is therefore considering the microbial metabolism (biomass oxidation, endogenous respiration, nitrification ...) based on the biodegradable organic fraction of the wastewater, biomass yield, decay coefficients, temperature, and aeration rates. In this study, the model predicted a value of 0.325 kg CO₂/m³. The resulting outcomes for the other emissions (2.15 · 10⁻³ kg N₂O/m³ and 6.19 · 10⁻³ kg CH₄/m³) are in line with previous studies [39], such as 3.0 · 10⁻³ kg N₂O/m³ and 7.50 · 10⁻³ kg CH₄/m³.

2.3.3. Life cycle impact assessment: method and categories selection

The Life Cycle Impact Assessment (LCIA) phase converts the elementary flows derived from the LCI of the wastewater treatment process into quantifiable environmental impacts, which are subsequently analyzed in the interpretation phase [42]. The SimaPro® v10.1.0.6 software was used to support this transformation.

Environmental impact characterization was performed using the ReCiPe Midpoint v1.07 method, following a hierarchical (default) time perspective. From the full set of ReCiPe Midpoint impact categories, eight were selected based on their relevance to wastewater treatment processes. This selection is supported by findings from systematic reviews of recent LCA studies [12]. The chosen categories included climate change (CC), ozone depletion potential (ODP), and ionizing radiation (IR), which are strongly influenced by electricity consumption, one of the main contributors to WWTP environmental footprints. These categories account for indirect emissions from electricity production, including greenhouse gases, ozone-depleting substances, and radioactive releases from nuclear sources [43,44]. Additionally, marine eutrophication (ME) and freshwater eutrophication (FWE) were included due to their link with nutrient discharges (phosphorus and nitrogen) into water bodies (rivers or oceans), aligning with nutrient traceability criteria. Mineral resource scarcity (MRS) and fossil resource scarcity (FRS) were also included, considering the use of non-renewable materials and resources in plant operation and maintenance. Water consumption (WC) was also considered, as this category evaluates the effects of water use on aquatic and terrestrial ecosystems and plant species, with a focus on regions experiencing water scarcity [45].

2.4. Sensitivity analysis

A sensitivity analysis was performed to assess the robustness and relevance of the LCA results and to support sustainability-oriented decision-making [46]. The study focused on the replacement of the electrical country mix, as electricity was identified as the main contributor to environmental impact, and on the selection of treatment chemicals.

When it comes to the energy supply, the reference European electricity mix was replaced by the national energy profiles of all European countries (which reflect not only differences between geographical location but also proportions of renewable and fossil energy). The second aspect of the analysis addressed the environmental implications of replacing the primary coagulant PAC with alternative products available in the database: ferric chloride (FeCl₃), aluminum chloride (AlCl₃), and aluminum sulphate (Al₂(SO₄)₃). Within the second approach, the BioWin™ model was used to assess how the substitution of the primary coagulant affected the composition and quality of the treated effluent. The effluent concentrations predicted for each coagulant scenario were subsequently incorporated into the life cycle inventory as direct emissions to the receiving water body. This integration enabled a consistent comparison of the overall environmental performance of each alternative, identifying potential substitutes capable of improving the environmental profile of the wastewater treatment plant without compromising operational efficiency. To ensure comparability

among scenarios, the same coagulant dosage applied in the baseline PAC case was maintained.

3. Results

3.1. Operational performance from inventory data

The WWTP analyzed in this study has a total energy consumption of approximately 6 kWh/m³, with the SBR reactor being the main

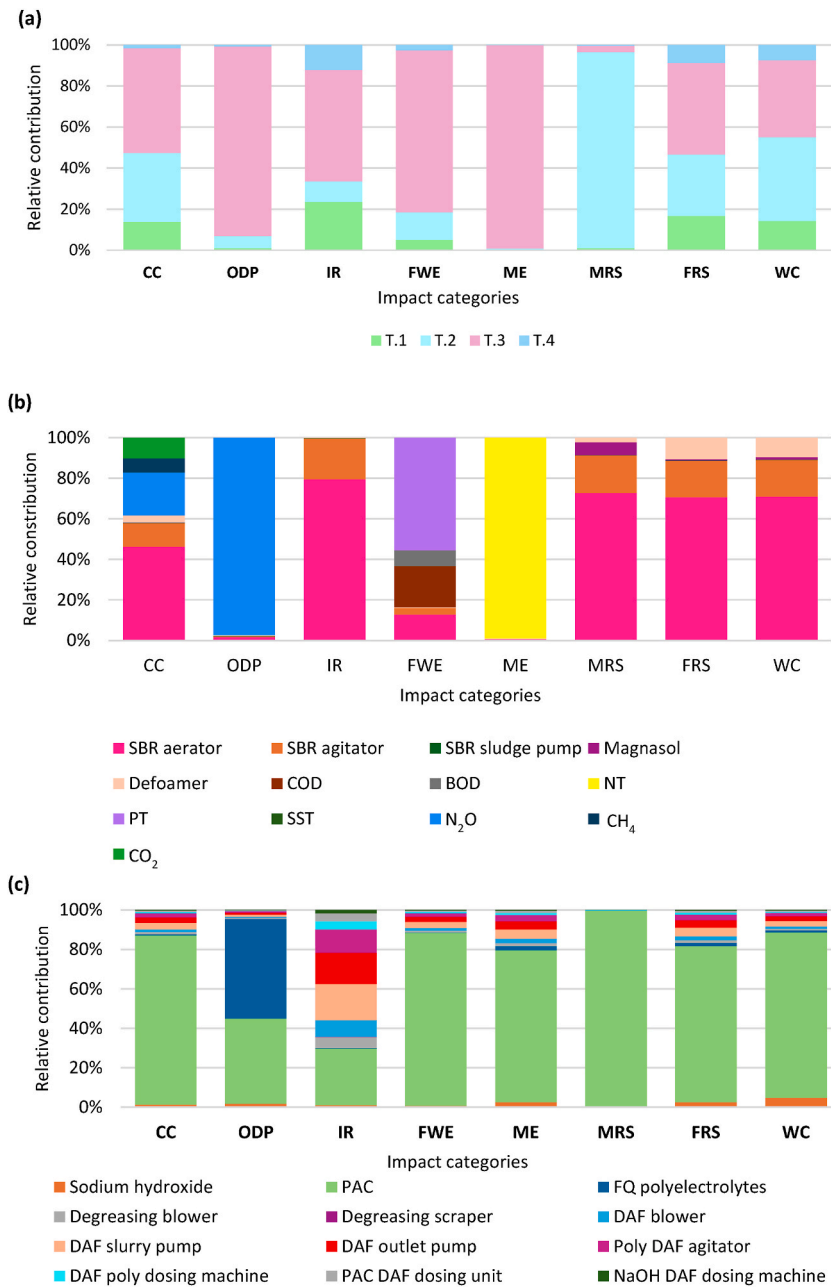


Fig. 3. Relative contribution of the cannery wastewater treatment plant by stage (pretreatment, primary, secondary, sludge line) (a), for the steps of the secondary stage (b) and the breakdown of the primary stage (c). BOD: Biochemical Oxygen Demand; CC: Climate Change; COD: Chemical Oxygen Demand; DAF: Dissolved air flotation; FQ: Physico-chemical treatment; FRS: Fossil Resource Scarcity; FWE: Freshwater Eutrophication; IR: Ionizing Radiation; NaOH: Sodium hydroxide; ME: Marine Eutrophication; MRS: Mineral Resource Scarcity; ODP: Ozone Depletion potential; PAC: Poly-aluminum chloride; SBR: Sequencing Batch Reactor; TN: Total nitrogen; TSS: Total Suspended Solids; TP: Total phosphorus; T.1: Pretreatment; T.2: Primary Treatment; T.3: Secondary Treatment; T.4: Sludge Line; WC: Water Consumption.

contributor (3.53 kWh/m^3) and accounting for about 59% of the total electricity demand. This finding aligns with results reported by Liao et al. [47], who found that the biological treatment stage can account for up to 66.3% of the total energy consumption in WWTPs. Aeration systems are the primary energy consumers in aerobic batch biological processes, with reported values reaching up to 3.80 kWh/m^3 in industrial applications [48]. Additionally, the energy consumption of the SBR process has been shown to increase significantly with higher organic loads [49]. In this study, the influent COD is approximately five times higher than the typical 1000 mg/L concentration found in conventional municipal wastewater, which explains the large energy demand in the SBR unit.

The operation of WWTP requires various chemicals (as shown in Table 2), mainly used in the primary treatment and sludge lines. According to the life cycle inventory data, the most consumed chemical is PAC, with an estimated usage of 18.72 kg/d . PAC is widely used in wastewater treatment due to its high solubility in water, fast floc formation, effectiveness at low doses, and efficiency across a broad pH range [50].

Direct emissions include pollutants to both air and water, which are environmentally relevant due to their potential impacts. Among air emissions, CO_2 stands out as the dominant GHG, with an emission of 32 g/m^3 , compared to 6.2 and 2.1 g/m^3 of CH_4 and N_2O , respectively. For waterborne emissions, COD is the most abundant parameter (0.11 kg/m^3), followed by TN at 39 g/m^3 and BOD at 39 g/m^3 . TP and TSS are also present at concentrations of 7 g/m^3 and 0.11 kg/m^3 , respectively. Despite these values, the treated effluent complies with the discharge limits established for this specific facility, as detailed in Section 2.1.2 (Water line).

3.2. Hotspots analysis

An integrated assessment was carried out at the level of the entire system, considering all treatment units simultaneously (Fig. S1). The results show that electricity consumption is the main driver of impact in categories such as CC, IR, FRS and WC, reflecting the energy intensity of the biological process. In contrast, the ODP category is dominated by emissions to air, while FWE and ME are clearly determined by emissions to water. For its part, MRS shows a predominant contribution from the consumption of chemical reagents, highlighting the influence of physicochemical treatment in this category.

Fig. 3a shows the relative contribution of each process stage (pretreatment, primary treatment, secondary treatment, and sludge treatment) to the different environmental impact categories assessed in the life cycle analysis. These results are based on the operational data collected from the actual facility, prior to the development of the digital twin. Secondary treatment is the dominant contributor in most scenarios, particularly in ODP (92%), CC (51%), FWE (70%), and ME (99%). Primary treatment shows a major contribution in the MRS category, accounting for 96%. Sludge and pretreatment stages consistently contribute less to all categories, with primary treatment never exceeding 24% and sludge treatment staying below 12%.

A further interpretation of the results with Fig. 3b, which is per impact distribution by category for secondary treatment, indicates that the SBR aerator is the most energy-intensive equipment, also contributing the highest share to several impact categories: IR (79%), FRS (69%), MRS (58%), CC (46%), and WC (70%). The CC impact associated with the SBR reached $3.98 \text{ kg CO}_2\text{-eq./m}^3$, which is comparable to the $4.2 \text{ kg CO}_2\text{-eq./m}^3$ reported by Gilad et al. [51] for an SBR system in South Africa.

In the ODP category, 97% of the total impact is attributed to N_2O , a greenhouse gas with a high ozone depletion potential. According to the IPCC [52], SBRs show high specific N_2O emission rates with emission factors around $0.023 \text{ kgN}_2\text{O-N/kg N}$ treated. These emissions are strongly influenced by the aeration regime and the DO concentration in the SBR. Low DO conditions can favor

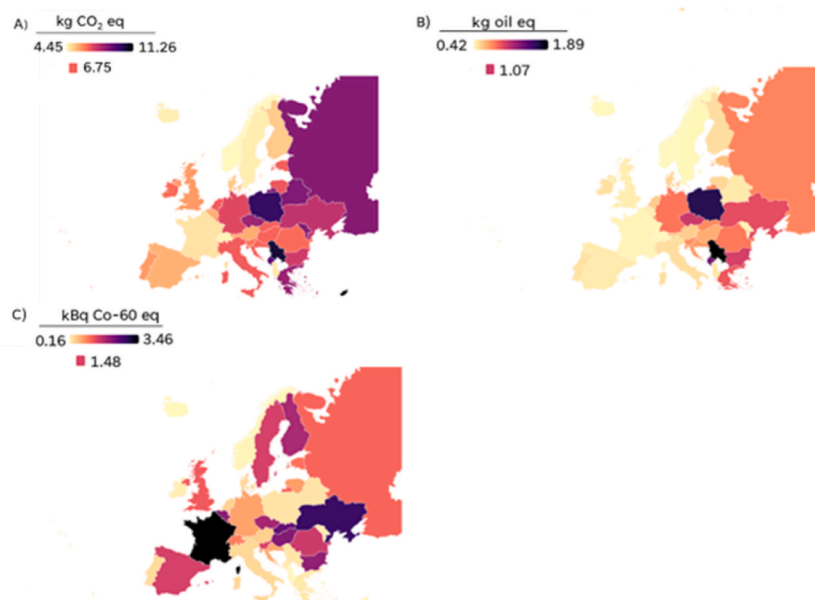


Fig. 4. Comparison of the environmental performance for climate change (a), fossil resource scarcity (b) and ionizing radiation (c).

incomplete nitrification and promote N_2O accumulation via the nitrifying denitrification pathway, while excessive aeration increases energy consumption without improving treatment efficiency. Maintaining adequate DO levels is therefore essential to balance biological performance and energy demand. A previous study has shown that optimized DO control can simultaneously reduce N_2O emissions and improve aeration efficiency in biological nutrient removal systems [53]. This highlights the potential of operational strategies based on DO management as an effective way to mitigate both environmental and energy impacts in SBR systems. In the FWE and ME categories, the main impact drivers are the concentrations of residual nutrients in the effluent. For ME, total nitrogen accounts for 99% of the impact, while for FWE, total phosphorus is the primary contributor (59%). For comparison purposes, when river emissions were excluded, the impacts of freshwater and marine eutrophication decreased by 65% and 98%, respectively, while the remaining impact categories were unaffected and electricity consumption continued to dominate the environmental profile.

The analysis of the primary treatment (Fig. 3c) focuses on the relative contribution of the chemicals and equipment directly associated with the DAF system and the degreasing unit. Results indicate that chemical consumption is a major contributor to the environmental impact across several categories, with PAC identified as the principal hotspot. Its contribution is especially high in CC (86% of chemical-related impact), FRS (79%), ME (77%), MRS (100%), FWE (88%), and WC (84%). In the ODP category, the impact is split between PAC (43%) and polyelectrolytes (51%), while in the IR category, PAC accounts for 44% of the total impact.

3.3. Sensitivity analysis

3.3.1. Impact of electricity mix on environmental performance

The baseline scenario corresponds to the average European electricity mix used in the inventory. Thematic maps were used to visualize the results (Fig. 4) highlighting the influence of the electricity mix on the environmental profile. Four relevant impact categories were presented: CC, IR, FRS. The color gradient indicates the performance of each country with the darker shades reflecting the higher impacts.

In the case of CC (Fig. 4a), a total of 18 European countries present values below the baseline scenario of $6.75 \text{ kg CO}_2\text{-eq./m}^3$ (see Table S6). Overall, the potential range of variation spans from 4.45 to $11.26 \text{ kg CO}_2\text{-eq./m}^3$, showing that the same facility could exhibit more than a twofold variation in climate impact depending solely on the electricity source. The most significant reductions compared to the European average were observed in Norway (−34%), Switzerland (−33%), Iceland (−32%), Sweden (−31%), and France (−28%), where renewable or low-emission sources dominate [54–56]. Countries like Portugal (−12%), Denmark (−22%), Spain (−17%), Austria (−15%), Ireland (−2%), Italy (−1%), and the UK (−11%) also show moderate but meaningful improvements (Fig. 4a).

In contrast, several countries show impacts above the reference value. The largest increase occurs in Cyprus, where the climate impact rises to $11.26 \text{ kg CO}_2\text{-eq./m}^3$ (+66%). Serbia (+56%) and Poland (+47%) follow, reflecting their strong dependence on fossil fuels [57]. Montenegro (+38%), Russia (+28%), and Greece (+24%) also present notable increases above the European average.

Beyond climate change, LCA sensitivity analysis reveals significant variations in other environmental categories. In FRS (Fig. 4b),

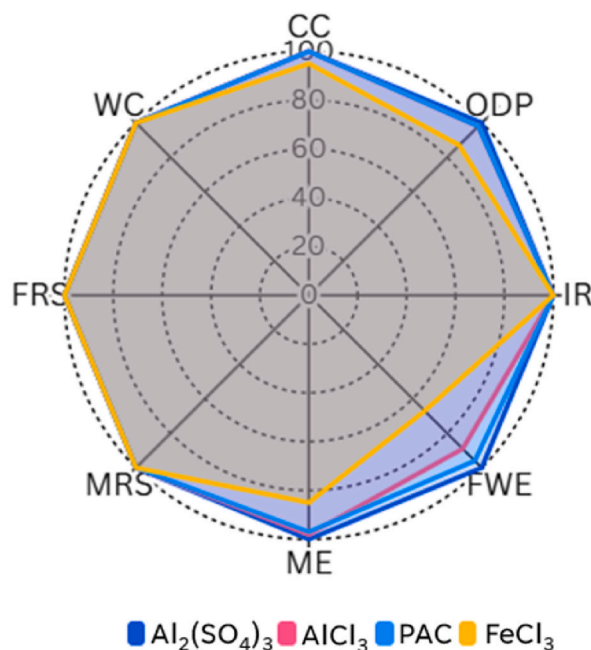


Fig. 5. Sensitivity analysis of environmental impacts associated with coagulant selection. CC: Climate Chang; FRS: Fossil Resource Scarcity FWE: Freshwater Eutrophication; IR: Ionizing Radiation; ME: Marine Eutrophication; MRS: Mineral Resource Scarcity; ODP: Ozone Depletion potential; WC: Water Consumption.

substantial reductions are seen in countries with a high share of renewables, such as Norway (−61% vs. baseline of 1.07 kg oil-eq./m³). Conversely, in Serbia and Poland, this impact increases by 77% and 56%, respectively, reflecting the fossil fuel dominance in energy matrix of Eastern Europe [58].

For the IR category (Fig. 4c), results are strongly influenced by nuclear energy presence. France, where over 69% of electricity comes from nuclear sources [59], shows the highest impact at 3.46 kBq Co-60 eq./m³ a 134% increase from the plant baseline (1.48 kBq Co-60 eq./m³). High values also appear in Ukraine, Slovakia, Hungary, and Bulgaria. In contrast, countries with low or no nuclear contribution such as Iceland and Norway show over 80% reductions [60].

The results obtained show that the national electricity profile is a determining factor in the environmental impacts of the industrial WWTP evaluated. This behavior is not unique to our case study but rather responds to structural trends previously identified in literature. For example, Ewertowska et al. [61] combined LCA and Data Envelopment Analysis (DEA) approach to assess the eco-efficiency of the electricity mixes of the main European economies, concluding that countries with a high proportion of hydro-electric power (such as Norway) or low dependence on nuclear power (such as Ireland and Romania) perform significantly better environmentally than those with a high share of fossil fuels.

3.3.2. Impact of alternative coagulants on environmental performance

The sensitivity analysis showed that replacing PAC coagulant with FeCl₃ generates significant improvements in both the operational performance of the system and its overall environmental footprint (Fig. 5). In simulations carried out with BioWin™, the stoichiometric adaptation of the coagulant resulted in lower concentrations of phosphorus and nitrogen in the treated effluent. These operational changes are reflected in reductions of 33% in FEW and 15% in ME, demonstrating an improvement in the performance of the operation of the plant. From the perspective of the indirect impacts derived from the production and supply of coagulants, FeCl₃ showed a more favourable environmental profile than aluminium-based products. In particular, the climate change category decreased from 7.10 to 6.75 CO₂ eq./m³, representing an absolute reduction of 0.35 kg CO₂ eq./m³ compared to the baseline scenario. This improvement is due to the lower energy intensity and emissions associated with the manufacture of ferric chloride. Decreases were also observed in ODP (−13%) and FRS (−5%), linked to the reduced use of fossil fuels in its production chain.

In contrast, aluminum-based coagulants did not show any significant environmental benefits. AlCl₃ showed a slight improvement in FWE (−8%), although with slight increases in ODP (+2%) and ME (+3%). Al₂(SO₄)₃ recorded the highest impacts in almost all categories, confirming its lower overall environmental performance.

Overall, the results confirm that FeCl₃ is the most sustainable alternative, combining operational improvements derived from the treatment process with a lower environmental impact in its production. This behavior coincides with the findings of Umar et al. [62], who reported that ferric chloride has a lower global warming potential than aluminum-based coagulants due to lower greenhouse gas emissions throughout its life cycle.

4. Conclusions

This study applied a combined approach of dynamic simulation and LCA to evaluate the environmental performance of an industrial wastewater treatment plant in the fish canning sector. Using detailed modelling in BioWin™, it was possible to replicate the operation of a real facility treating effluents with high organic and nutrient loads. The digital model supported the analysis of coagulant substitution scenarios, providing site-specific data for assessing the environmental trade-offs of using alternative chemicals under equivalent dosing conditions.

The LCA revealed that electricity consumption, especially in the SBR, is the main environmental hotspot, significantly affecting categories such as climate change, ozone depletion, and ionizing radiation. Sensitivity analysis with different national electricity mixes identified substantial improvement potential, with climate change impact reductions of up to 34% in countries with cleaner energy matrices, such as Norway and Iceland. This highlights the importance of accounting for electricity origin in environmental assessments of energy-intensive systems.

Additionally, the coagulant comparison showed that ferric chloride is a potentially more sustainable alternative to PAC, reducing impacts in several categories, including climate change, eutrophication, and ozone depletion. These improvements may be linked to a smaller environmental footprint throughout its life cycle and better phosphorus removal efficiency.

Overall, the findings identify specific opportunities for environmental improvement regarding both chemical inputs and energy supply. The integration of simulation models with LCA methodologies proves to be a key tool for optimizing environmental sustainability in the design and operation of industrial wastewater treatment plants. Looking ahead, it would be valuable to evaluate the integration of energy recovery processes that contribute to reducing the impacts associated with electricity consumption, as well as to optimize aeration control in the SBR through improved DO management, which could improve energy efficiency without affecting treatment performance. Furthermore, the analysis of alternative sludge management and recovery strategies, particularly composting, could contribute to improving the overall circularity and sustainability of the system.

CRedit authorship contribution statement

Belinda Cendan: Writing – original draft, Software, Methodology, Investigation, Data curation. **Ana Arias:** Writing – review & editing, Visualization, Validation, Supervision. **Sofía Estévez:** Supervision, Visualization, Writing – review & editing. **Priscila Artiga:** Validation, Data curation. **Gumersindo Fejoo:** Writing – review & editing, Visualization, Validation, Supervision. **María Teresa Moreira:** Writing – review & editing, Visualization, Validation, Supervision.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wri.2026.100361>.

Data availability

Data will be made available on request.

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