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Life cycle assessment of valorisation processes for industrial saline residues

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ABSTRACT

Scaling up emerging technologies for industrial wastewater treatment faces a key challenge: the lack of comprehensive environmental impact assessments at both pilot and full-scale levels. Although these technologies show promise, their implementation may cause environmental impacts equal to or greater than those from conventional processes. Life Cycle Assessment (LCA) is a powerful tool for evaluating and comparing the environmental performance of alternative treatment and reuse strategies. This study applies LCA to assess the environmental impacts of valorising industrial saline residues from the tanning and codfish processing industries by treating and reusing the resulting brine in the pickling process of the tanning industry, replacing virgin brine. A comparison with a baseline representing current practices is also conducted. In particular, for the tanning industry, the baseline scenario considers that contaminated curing salt is disposed of in landfills and virgin brine is used in the pickling process. In the valorisation scenario, the contaminated curing salt is dissolved in tap water to produce brine, which is then treated by electrocoagulation for reuse in the pickling process. For the codfish processing industry, the baseline scenario considers that contaminated brine is discharged to a wastewater treatment plant and virgin brine is used in the pickling process. In the valorisation scenario, contaminated brine is treated by electro-Fenton process and subsequently reused in the tanning pickling process.

Results show that the pickling process contributes significantly to the environmental burdens, primarily due to the use of chemicals, with limited benefits observed from simple brine replacement. However, valorising contaminated salt from the tanning industry markedly reduces impacts in all impact categories (5–32%), not only from the replacement of virgin salt use in the pickling process, but mainly from avoiding landfilling of contaminated salt. Treating codfish brine offers even greater benefits, with reductions up to 88% in freshwater eutrophication impacts due to the avoidance of discharging treated brine into freshwater aquatic environments. However, some categories worsen slightly mainly due to increased impacts from the electro-Fenton treatment. This comparative LCA provides valuable insights for sustainable technology implementation and supports more informed industrial decision-making.

1. Introduction

The tanning industry has long been associated with substantial environmental impacts (Annamalai et al., 2022; Sarinho et al., 2023). Worldwide, the sector produces approximately 800,000 t of finished leather annually and is responsible for generating around 600 L of wastewater per hide processed (Michael Black et al., 2013; Rebelato et al., 2024). Although the industry valorises byproducts from the meat sector, such as raw hides and skins, to produce value-added products for the fashion market, it remains heavily dependent on the consumption of water and chemicals to achieve the desired properties of finished leather (Michael Black et al., 2013; Pasquali et al., 2025). Consequently, increasing attention has been given to the development of cleaner production approaches aimed at reducing the environmental footprint of tanning operations (Aquim et al., 2019; Pasciucco et al., 2025; Sarinho et al., 2023).

One of the significant streams of this industry is the contaminated salt generated during the curing stage. It is estimated that approximately 0.3–0.5 kg of curing salt is generated per kilogram of raw hide processed, corresponding to nearly 250,000 t annually worldwide impacts

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(Annamalai et al., 2022). At this point, the salt becomes contaminated with animal manure, hair, blood, and other residues, leading to the common practice of landfilling this material. However, this practice poses risks such as soil and groundwater contamination and limits landfill biogas production by disrupting microbial degradation processes (Ogata et al., 2016). Another critical stage in the tannery process is the pickling process, which requires significant amounts of both water and salt (Husain et al., 2025a). However, if the contaminated salt from the curing stage is properly treated, it could potentially be reused within the industry during the pickling process, thus minimising environmental impacts and reducing resource consumption (Sarinho et al., 2023).

Environmental challenges related to waste management are not unique to the tanning industry but are also prevalent in other sectors. One such example is the seafood industry, particularly in the processing of codfish, which generates saline wastewater, commonly referred to as brine.

This brine is characterised by high sodium chloride (NaCl) concentrations, typically ranging from 150 to 300 g/L, as well as elevated chemical oxygen demand (COD) values exceeding 10,000 mg/L (Panagopoulos, 2022a, 2022b). These conditions are considerably above the inhibitory thresholds for biological treatment in conventional wastewater treatment plants (WWTPs), where salinity levels above 3000 mg/L NaCl may already compromise microbial activity. Consequently, the discharge of large quantities of brine can negatively affect WWTP performance and contribute to the loss of potentially valuable resources (Mavukkandy et al., 2019; Partal et al., 2022). Therefore, brine requires careful management to minimise its environmental impact (Feizi et al., 2024; Rodrigues et al., 2021; Sarinho et al., 2025).

Increased salinity tends to inhibit microbial activity, and at higher concentrations, it can severely restrict biological treatment methods, rendering them ineffective (Panagopoulos, 2022a; Souli et al., 2023). A promising strategy to reduce the burden on WWTPs is the valorisation of brine, transforming it into a valuable resource that can be repurposed in other industrial processes, such as the tanning industry.

Recent advances in the treatment of industrial saline residues have demonstrated promising valorisation potential. Sarinho et al. (2023) reported the successful treatment of contaminated hide-curing salt by electrocoagulation, while Sarinho et al. (2025) demonstrated the effective treatment of codfish processing brine by electro-Fenton. In both cases, the recovered saline streams were subsequently reincorporated into the leather pickling process without compromising the quality of the resulting wet-blue leathers, as assessed through standard quality parameters, including thickness, shrinkage temperature, grease content, free fatty acids (FFA), and chromium oxide (Cr_2O_3) content in accordance with ISO 5433 (2013).

Beyond the leather industry, similar valorisation strategies have been explored in other industrial contexts. Roibás-Rozas et al. (2023) evaluated the production of value-added bioproducts, namely polyhydroxyalkanoates (PHA) and triacylglycerides (TAG), from saline wastewaters generated by seafood processing industries using mixed microbial cultures, demonstrating that the recovery and reuse of saline streams can reduce environmental impacts, lower wastewater treatment burdens, and improve the economic sustainability of industrial processes. Complementing these findings, Chen et al. (2025) conducted a comparative techno-economic analysis of two alternative valorisation strategies for saline industrial wastewaters, namely impurity removal followed by salt extraction and recovery, and impurity removal combined with electrolysis to generate value-added products. They concluded that both approaches can effectively transform saline wastewater into valuable resources while supporting circular economy principles and reducing the environmental burden associated with conventional disposal practices.

These findings highlight the feasibility of cross-industry valorisation of waste products, thereby supporting more sustainable practices in both sectors. These recovery pathways are aligned with circular economy principles, particularly through the valorisation of saline residues as secondary resources. Moreover, the reuse of treated codfish brine in leather processing represents a potential industrial symbiosis strategy, in which waste generated by one industrial sector can be utilised as a resource by another. Such approaches may contribute to reducing waste disposal, decreasing the consumption of virgin salt, and improving resource efficiency across industrial systems. Therefore, the integration of saline residue recovery processes into industrial operations has the potential to support the transition towards more circular and sustainable production models.

However, to ensure the environmental sustainability of innovative approaches, a comprehensive environmental assessment must be conducted. Addressing this gap requires a detailed Life Cycle Assessment (LCA) of the proposed treatment processes. LCA follows a “cradle-to-grave” approach (ISO 14040), making it particularly effective for such evaluations (Fernández-Torres et al., 2012).

Given the potential of LCA in supporting sustainable decision-making (Ribeiro et al., 2024), research efforts have notably increased in recent years, particulary focused on promoting more sustainable production practices, while scientific interest in the environmental management of saline waste has also grown (Abyar et al., 2025; Fernández-Torres et al., 2012; Zhang et al., 2018). However, despite the increasing attention, only a limited number of LCA studies have been conducted for the tanning and codfish industries (Batista et al., 2025; Husain et al., 2025b; Roibás-Rozas et al., 2023). Notably, there is a significant gap in research focused on the treatment of saline waste from both sectors, particularly concerning its potential reuse in industrial processes.

Building on recent research on saline residue valorisation (Sarinho et al., 2025, 2023), this study uses LCA to evaluate the environmental performance of two strategies aimed at replacing virgin brine used during the pickling process in the tanning industry with treated brine recovered from industrial processes. Both industries are examined as distinct manifestations of a shared industrial challenge, namely the generation of contaminated saline residues with valorisation potential.

As illustrated in Fig. 1, the first strategy consists of an internal valorisation approach within the tanning industry, in which brine is recovered through the electrocoagulation treatment of contaminated curing salt. Since the pickling stage inherently requires salt dissolution, electrocoagulation was applied to the brine solution rather than to the solid salt, thereby preserving the saline properties relevant to the subsequent process. The second strategy explores an industrial symbiosis approach between the codfish processing and tanning industries, in which brine is recovered through the electro-Fenton treatment of saline effluents from codfish processing. These two case studies represent complementary circular economy approaches for saline residue recovery and reuse. In this context, this study aims to determine whether these recovery strategies constitute environmentally preferable alternatives to conventional practices in these industries, as well as to identify the main environmental hotspots associated with each strategy. The LCA is intended to support decision-making by stakeholders from the tanning and codfish processing industries, as well as policymakers and practitioners interested in circular economy and industrial symbiosis strategies. By assessing the environmental trade-offs and potential benefits of saline residue valorisation, the study contributes to the development of more circular and resource-efficient industrial systems.

2. Materials and methods

To evaluate the environmental performance of the processes under study, the LCA was conducted in accordance with the ISO 14040 and ISO 14044 standards.

2.1. System boundaries and functional unit

Two systems were analysed: one involving the treatment of contaminated curing salt from the tanning industry using

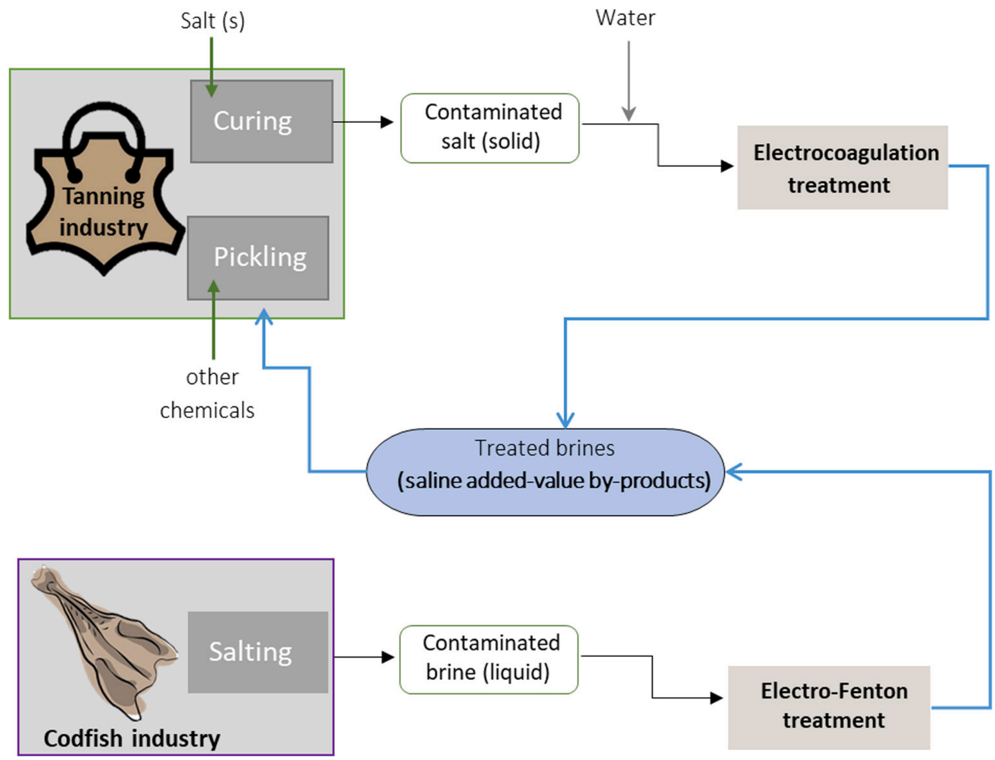

Fig. 1. Valorisation of saline residues from industrial processes for reuse in the pickling process of leather processing.

electrocoagulation (Fig. 2), hereinafter referred to as System 1; and the other involving the treatment of contaminated brine from codfish processing (Fig. 3), hereinafter referred to as System 2.

For each system, two scenarios were defined: the first, designated as Scenario A, represents the baseline situation, i.e., the current practices in both industries, while the second, designated as Scenario B, represents the proposed valorisation treatment. The baseline scenarios represent the existing waste management and disposal methods in the tanning and codfish sectors, serving as a reference for evaluating the potential environmental benefits of the proposed valorisation treatments.

In both systems, the treatment technologies perform a dual function: (i) the treatment of saline waste streams and (ii) the recovery of treated brine suitable for reuse in the pickling process. Therefore, the functional units were defined to reflect both functions delivered by the analysed systems. Since System 1 and System 2 address different waste streams and recovery contexts, distinct functional units were adopted for each case study. Consequently, the results are intended to support comparisons between Scenario A and Scenario B within each individual system,

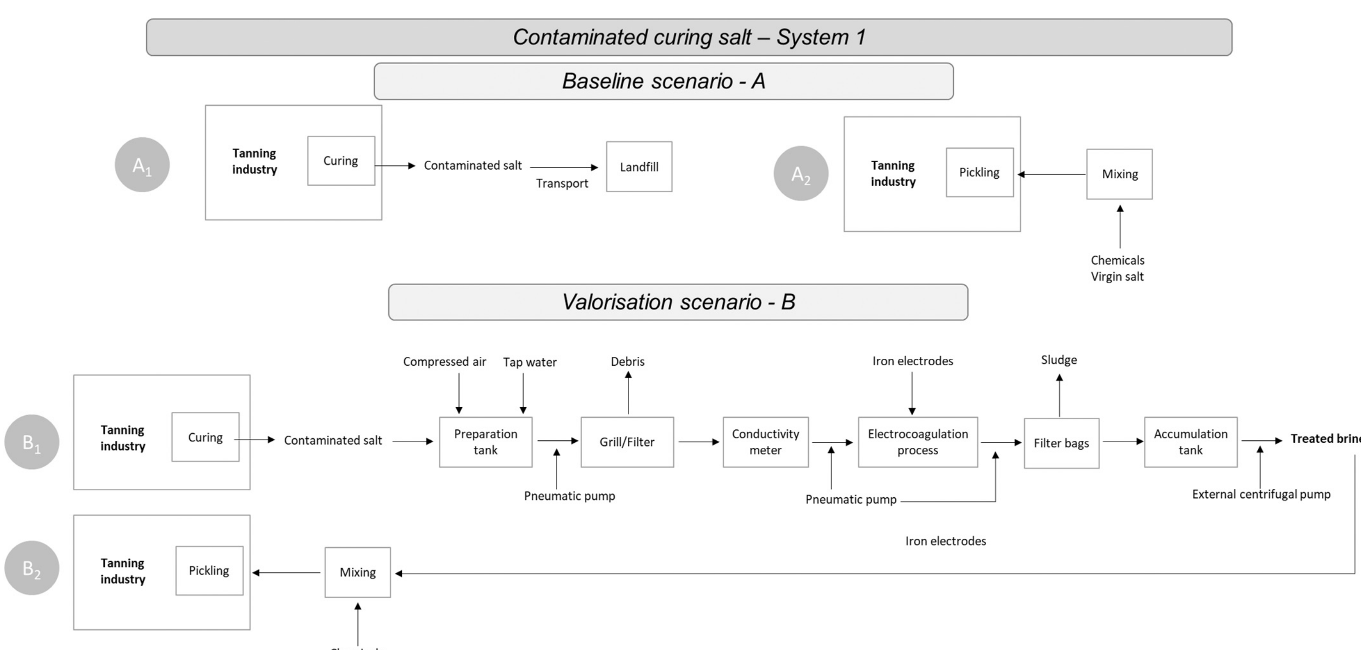

Fig. 2. Scheme of the system boundaries considered in the scenario of contaminated curing salt.

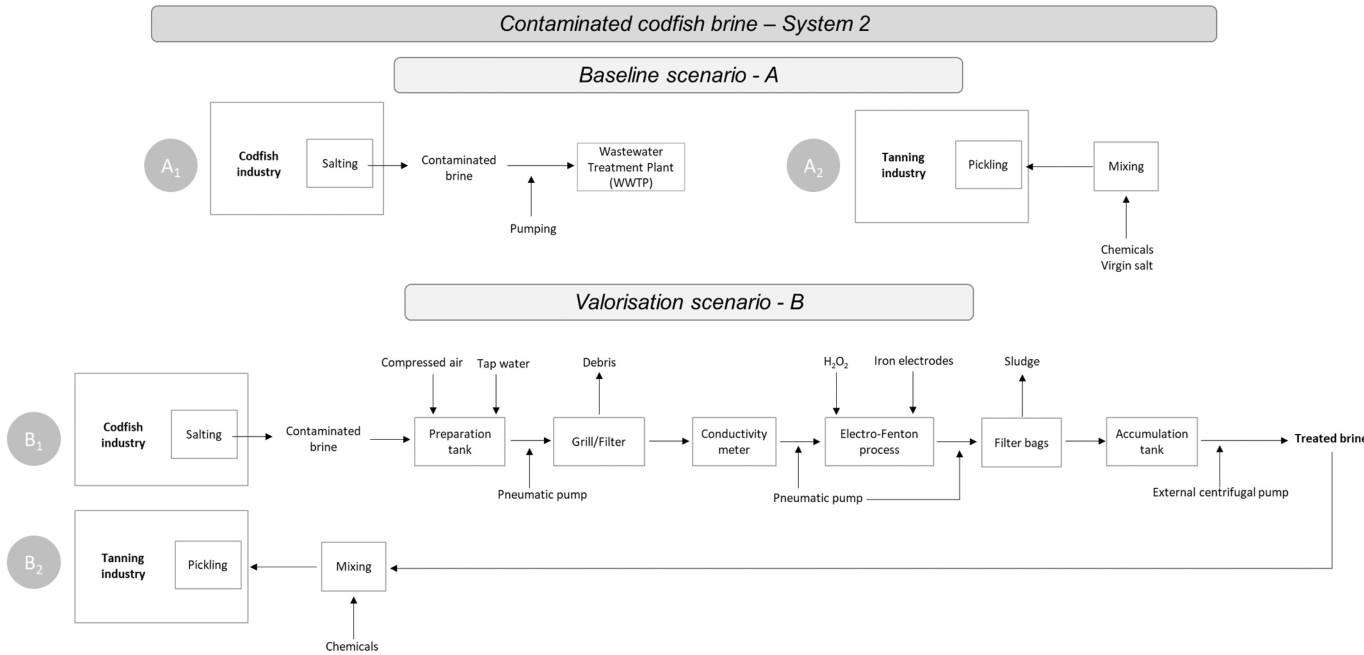

Fig. 3. Scheme of the system boundaries considered in the scenario of contaminated codfish brine.

rather than direct comparisons between the absolute environmental impacts of the two systems.

2.1.1. *Curing salt – System 1*

Fig. 2 illustrates the system boundaries defined for the curing salt case study, in which two subsystems were considered in both scenarios. In Scenario A (baseline), subsystem A_1 corresponds to the landfilling of contaminated salt waste generated during the curing stage, while subsystem A_2 represents the pickling process in the tanning industry using virgin salt. In contrast, Scenario B (valorisation) includes subsystem B_1, which involves the treatment of the contaminated salt waste through an electrocoagulation process. The resulting treated brine is then used in subsystem B_2, replacing virgin salt in the pickling process. The analysis does not include the production or maintenance of capital goods (e.g., buildings and equipment).

To ensure comparability between scenarios within System 1, the functional unit was defined as the final disposal or treatment of 1 kg of contaminated salt and the supply of 0.0029 m^3 of brine for the pickling process. This amount of brine corresponds to the quantity recovered through the electrocoagulation treatment of 1 kg of contaminated curing salt. This functional unit ensures that both scenarios deliver equivalent functions.

2.1.2. *Codfish brine – System 2*

The codfish brine case study is outlined in Fig. 3. This system also considered two distinct scenarios, each composed of two subsystems. In Scenario A, A_1 corresponds to the treatment of contaminated brine from the codfish industry in a conventional WWTP. Subsystem A_2 adopts the same approach described in Section 2.1.1, with the use of virgin salt in the pickling process. In Scenario B, the contaminated brine is treated through electro-Fenton process (subsystem B1), and the resulting treated brine is subsequently applied in the pickling process, replacing the need for virgin salt (subsystem B_2). As for System 1, production and maintenance of capital goods were excluded.

To ensure comparability between the two scenarios within System 2, the functional unit was defined as the final disposal or treatment of 1 m^3 of contaminated brine and the supply of 1 m^3 of brine for the pickling process. This amount of brine reflects the quantity of treated brine recovered through the electro-Fenton treatment of 1 m^3 contaminated brine from the codfish industry, thereby ensuring functional equivalence between the compared scenarios.

2.2. *Life cycle inventory*

The life cycle inventory was developed using a combination of primary and secondary data. Experimental data were collected from an electrocoagulation system at pilot scale, used to treat salt-derived brine, detailed in Section 2.2.1, and from an electro-Fenton process operated at bench scale, treating contaminated codfish brine, described in Section 2.2.2. These data included material and energy inputs, treatment efficiency, and emissions. For Scenario A (baseline scenario), the foreground data were derived from real operational reports provided by a tanning company and a codfish processing company for the year 2023, representing current industrial practices. Background processes such as electricity supply, reagent production, transportation, and waste disposal were modeled using datasets from the ecoinvent v3.11 database (Wernet et al., 2016) within SimaPro 10.3.0.1. Country-specific datasets for Portugal were used whenever available, namely for electricity production. In the absence of Portuguese datasets, European datasets were selected, while global datasets were used only when neither Portuguese nor European datasets were available. For materials for which specific transportation distances were available, "transformation" datasets were selected, and the corresponding transport processes were explicitly added to the system. In contrast, when transportation profiles were unknown, "market" datasets were used.

2.2.1. *Curing salt – System 1*

2.2.1.1. A_1 - Disposal of contaminated salt from the tanning industry in a landfill. The contaminated salt generated during the leather curing process is transported to a landfill located 5 km from the processing site. Transportation is carried out using a truck with a gross vehicle weight of less than 3.5 t. The inventory data associated with the truck's operation were sourced from the Ecoinvent 3.11 database (dataset presented in the Supplementary Information in table S3). Additionally, the inventory data for salt disposal at the landfill were modeled using the calculation tool for waste disposal on which the Ecoinvent datasets are based (Doka, 2021, 2003), taking into account the specific chemical composition of the salt (Table S1 of Supplementary Information).

2.2.1.2. A_2 - Pickling process using virgin salt. In the pickling process, hides are immersed in an acid brine solution, which sterilises and improves the penetration of subsequent tanning agents. Virgin salt is added to the solution to prevent and control skin swelling (Sarinho et al., 2023). The inventory data regarding the consumption and transportation of salt and chemicals, as well as electricity consumption, were provided directly by the tanning industry and are presented in Table 1. These data are expressed per 1 m^3 of brine, composed of 1 m^3 of water and 75 kg of salt. The inventory data for the production of salt, chemicals, and electricity, as well as for the operation of the transportation trucks, were obtained from the Ecoinvent 3.11 database. The datasets selected are presented in the Table S4 of the Supplementary Information.

2.2.1.3. B_1 - Treatment of contaminated curing salt through electrocoagulation process. In the treatment of contaminated curing salt by electrocoagulation, the salt is first transferred to a preparation tank, where it is diluted with tap water to a concentration of 30% wt. salt. The resulting brine is then pumped through a grid to remove larger solid residues (screenings) before being pumped into the tank where the electrocoagulation process takes place. During the electrocoagulation process, iron electrodes are used to generate coagulant in situ. After treatment, the brine passes through filter bags to remove the sludge produced during the electrocoagulation process. This sludge consists primarily of organic matter, with traces of iron and salt. The treated brine is subsequently transferred to an accumulation tank for storage prior to use. The inventory data for this process are presented in Table 2. Data related to the production of materials and electricity, as well as the operation of transportation truck, were sourced from the Ecoinvent 3.11 database. The datasets used are presented in the Table S5 of the Supplementary Information. Data related to waste disposal in landfill were sourced from the calculation tool mentioned previously (Doka, 2021, 2003).

2.2.1.4. B_2 - Pickling process using treated brine (with recovered brine). This subsystem, like the subsystem A_2, represents the pickling process, but in this case, treated brine from B_1 is used instead of virgin salt. Table 3 presents the inventory data for the pickling process of the tanning industry using treated brine, expressed per 1 m^3 of treated brine. Data related to the production of materials and electricity, as well as the operation of vehicles used in transportation, were obtained from the Ecoinvent 3.11 database (Table S6 of the Supplementary Information).

2.2.2. Codfish brine – System 2

2.2.2.1. A_1 - Treatment of contaminated brine from the codfish industry in a wastewater treatment plant. The codfish contaminated brine, a residue of the cod salting process, is characterised by high concentrations of organic matter and salt. It is diluted with other wastewater streams from the company and subsequently discharged into the municipal sewer system, where it is treated at a WWTP. In this process, the pumping of contaminated brine to the municipal sewer system requires an electricity consumption of 0.160 kWh per m^3 of contaminated brine. Of the total electricity used, 70% is sourced from the national grid, while the remaining 30% is supplied by on-site photovoltaic generation. The inventory data for electricity production were obtained from the Ecoinvent 3.11 database, using the datasets presented in the Table S7 of the Supplementary Information. The inventory data associated with the brine treatment process in the WWTP were modeled using the calculation tool mentioned above (Doka, 2021, 2003) considering the specific chemical composition of the brine (Table S2 of the of Supplementary Information).

Table 1
Inventory data for the pickling process with virgin salt.

Parameters	Quantity	Transportation distance (km)
Inputs		
Virgin salt (kg)	75	350
Water (m^3)	1	–
Sulfuric acid (kg)	36.2	200
Formic acid (kg)	23.3	3
Surfactant (kg)	14.8	217
Additive (kg)	1.8	217
Biocides (kg)	0.7	217
Grid electricity (kWh)	2.88	–
Photovoltaic electricity (kWh)	6.72	–

Table 2
Inventory data for the electrocoagulation treatment of contaminated salt from the tanning industry.

Parameters	Quantity	Transportation distance (km)
Inputs		
Water (m^3)	0.003	–
Iron electrodes (wear) (kg)	0.500	–
Filter bags (wear) (kg)	0.0084	–
Grid electricity (kWh)	1.820	–
Photovoltaic electricity (kWh)	4.240	–
Outputs		
Treated brine sent to pickling (m^3)	0.0029	–
Screenings for landfill (kg)	0.100	5
Sludge for landfill (kg)	0.002	5

Table 3
Inventory data for the pickling process with treated brine (instead of virgin salt).

Parameters	Baseline scenario	Transportation distance (km)
Inputs		
Treated brine (m^3)	1	–
Sulfuric acid (kg)	36.2	200
Formic acid (kg)	23.3	3
Surfactant (kg)	14.8	217
Additive (kg)	1.8	217
Biocides (kg)	0.7	217
Grid electricity (kWh)	2.88	–
Photovoltaic electricity (kWh)	6.72	–

2.2.2.2. A_2 - Pickling process using virgin salt. The description of Subsystem A_2 is provided earlier in Section 2.2.1.

2.2.2.3. B_1 -Treatment of contaminated codfish brine by electro-fenton process. The treatment of contaminated codfish brine by the electro-Fenton process begins with its pumping to a screen/filter to remove coarse residues. The brine is then pumped into the reactor, where the electro-Fenton occurs. During this process, iron electrodes are consumed (electrode wear) and hydrogen peroxide (H_2O_2) is used. Afterwards, the brine passes through filter bags to remove generated sludge and is finally directed to an accumulation tank as treated brine. In addition, the transportation of the brine by truck over a distance of 110 km from the codfish processing facility to the tanning facility was considered. The inventory data for the electro-Fenton process are presented in Table 4. Data concerning the production of materials and electricity, as well as the operation of trucks used in transportation, were retrieved from the Ecoinvent 3.11 database (Table S8 of the Supplementary Information). Data associated with the landfill disposal process were obtained from the previously mentioned calculation tool (Doka, 2021, 2003).

2.2.2.4. B_2 - Pickling process using treated brine (with recovered brine). Details regarding Subsystem B_2 are already presented in Section 2.2.1.

Table 4
Inventory data for the electro-fenton treatment of contaminated brine from the codfish industry.

Parameters	Quantity	Transportation distance (km)
Inputs		
Iron electrodes (wear) (kg)	0.259	–
Filter bags (wear) (kg)	2.300	–
Hydrogen peroxide (kg)	5.172	–
Grid electricity (kWh)	0.700	–
Photovoltaic electricity (kWh)	1.631	–
Outputs		
Treated brine sent to pickling (m^3)	1	–
Screenings for landfill (kg)	< 0.01	5
Sludge for landfill (kg)	0.172	5

2.3. Life cycle impact assessment

The environmental impacts were assessed in SimaPro 10.3.0.1 using the ReCiPe 2016 midpoint v1.01 method (Huijbregts et al., 2017). All 18 midpoint impact categories were calculated, and the complete results are provided in Section S3 and S4 of the Supplementary Information. The impact categories discussed in detail in this study include global warming (GW), ozone formation – human health (OFHH), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). These categories were selected due to their direct relationship with the main emissions and resource consumption associated with the analysed processes, while also covering impacts related to air emissions, water pollution, and resource depletion.

3. Results and discussion

3.1. Curing salt – System 1

Table 5 and Fig. 4 present the impact assessment results for each scenario. In scenario A, contaminated salt is disposed of in a landfill, and virgin salt is used in the pickling process. In contrast, scenario B involves treating the contaminated salt from the tanning industry, with the resulting brine being reused in the pickling process, eliminating the need for virgin salt. The results indicate that Scenario A consistently exhibits higher environmental impacts across all categories. In contrast, the valorisation scenario leads to a reduction in the environmental impacts, ranging from 9% for TA to 32% for ME. Relevant reductions are also achieved for FE (29%), MRS (25%), and GW (20%). Similar trends are observed for the remaining impact categories of the ReCiPe 2016 method, as presented in Table S9 of Supplementary Information. For these categories, the reductions in impacts range from 3% for land use to 36% for ionising radiation.

The pickling process dominates the environmental impact across all categories, including those presented in the Supplementary Information in section S3, in both scenarios, accounting for the majority of the total impacts. In Scenario A, it contributes between 66% and 97% of the total impacts, whereas in Scenario B, its contribution ranges from 95% to almost 100%. Landfill disposal of contaminated salt in the baseline scenario contributes a relatively small proportion to the overall environmental impact, with its maximum contribution, approximately 34%, occurring in the ME category. The use of virgin salt in the pickling process is associated with higher environmental impacts. In Scenario B, the impacts of the pickling process are reduced by between 2% (in ME) and 23% (in MRS) when the recovered brine is used instead of virgin salt. This reduction occurs because recovered brine enters the process without upstream impacts, unlike virgin salt. The environmental savings from replacing landfilling of contaminated salt with electrocoagulation treatment range from 70% (in MRS) to 90% (in OFHH and ME). An exception is observed for human carcinogenic toxicity (Fig. S1 in the Supplementary Information), where electrocoagulation treatment has a greater impact than landfilling of contaminated salt. This mainly results from the use of iron electrodes in the electrocoagulation treatment. These findings suggest that while the proposed changes offer significant environmental benefits, which are mainly associated with the avoidance of landfill disposal of contaminated salt, particularly for GW, OFHH, and ME, as well as with the partial substitution of virgin salt in the pickling process, for the remaining categories.

Table 5
Total impact of baseline (A) and valorisation (B) scenarios for curing salt.

	Scenario A	Scenario B
Global warming [kg CO_2 eq]	4.08×10^{-1}	3.83×10^{-1}
Ozone formation, Human health [kg NO_X eq]	1.14×10^{-3}	9.39×10^{-4}
Terrestrial acidification [kg SO_2 eq]	3.05×10^{-3}	2.79×10^{-3}
Freshwater eutrophication [kg P eq]	2.14×10^{-4}	1.52×10^{-4}
Marine eutrophication [kg N eq]	4.39×10^{-4}	2.97×10^{-4}
Mineral resource scarcity [kg Cu eq]	2.95×10^{-3}	2.20×10^{-3}
Fossil resource scarcity [kg oil eq]	1.40×10^{-1}	1.22×10^{-1}

Fig. 5 (a) shows that in the case of landfilling of contaminated salt, the landfill process is the dominant contributor to the environmental impacts across all categories, with contributions ranging from 51% for FRS to almost 100% for ME. For GW, FE, and ME, these impacts are mainly associated with direct emissions generated during waste decomposition in the landfill (methane, phosphorus, and nitrogen compounds, respectively). In the case of OFHH, TA, and FRS, the impacts arise primarily from diesel combustion in landfill machinery. Finally, for MRS, the impacts are mainly related to iron depletion associated with the use of iron chloride as a coagulant in leachate treatment. These trends are also observed for the remaining impact categories presented in the Supplementary Information (Fig. S2). The only exception is terrestrial ecotoxicity, for which the transport of contaminated salt to landfill contributes slightly more (52%) than the landfill disposal process itself.

In the electrocoagulation treatment (Fig. 5 (b)), the disposal of sludge and screenings in landfill is the main contributor to the environmental impacts across all categories, except MRS, accounting for between 41% (FRS) and 100% (ME) of the total impacts. The main causes of these impacts are similar to those identified above for the landfilling of contaminated salt. In MRS, the iron electrodes used in the process account for 63% of the total impact, mainly due to the depletion of iron. Electricity consumption is also a relevant contributor to TA and FRS, accounting for approximately 25% of the impacts, mainly due to sulfur dioxide (SO_2) and nitrogen oxide (NOx) emissions in TA, and natural gas depletion in FRS. It should be noted that approximately 27% of the grid electricity mix was generated from fossil fuels, primarily natural gas. These are also the main hotspots for the remaining impact categories presented in the Supplementary Information (Fig. S3). In the study by Sedaghat et al. (2025), the electrocoagulation process was applied to optimise wastewater treatment from the textile industry. They identified electricity consumption in the electrocoagulation system as the primary contributor to global warming and fossil fuel consumption. However, the impacts associated with electricity use are highly dependent on the sources of electricity. In the present study, photovoltaic energy presents a minimal overall environmental impact, highlighting its clean and renewable nature and emphasising its positive contribution to mitigating environmental burdens. In contrast, the use of grid electricity results in significantly higher impacts, likely due to its partial reliance on fossil fuel-based generation. Moreover, Sedaghat et al. (2025) also conclude that the use of electrode materials contributed notably to global warming impacts. In the present work, iron electrodes present a smaller contribution of around 15%, mainly due to carbon dioxide (CO_2) emissions associated with pig iron production, particularly from the combustion of fuels such as coal and coke. This impact could be further reduced if scrap metals were used as an alternative, thereby decreasing the environmental burden associated with

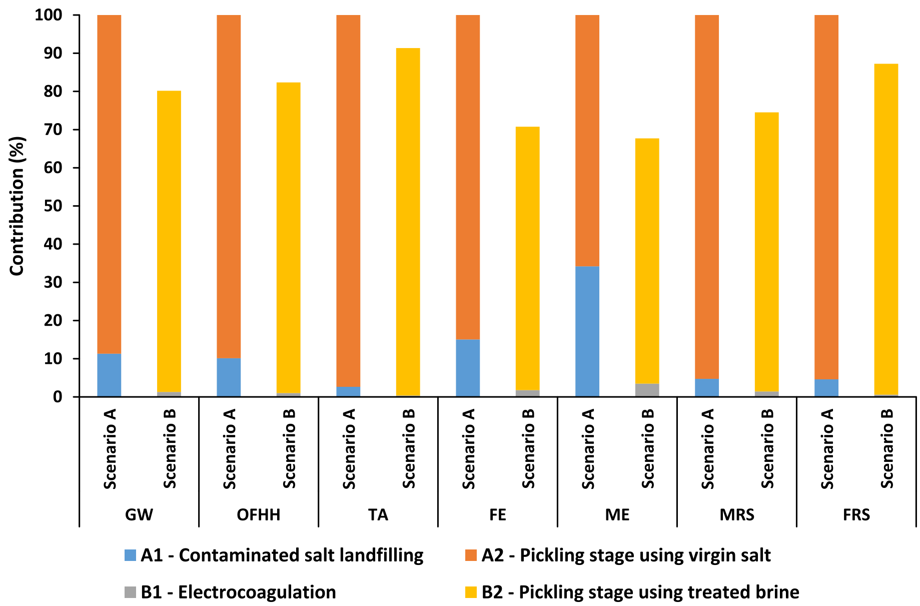

Fig. 4. Comparison between baseline (A) and valorisation (B) scenarios according to the key impact categories for curing salt. The scenario with the greatest impact in each category is assigned a value of 100%.

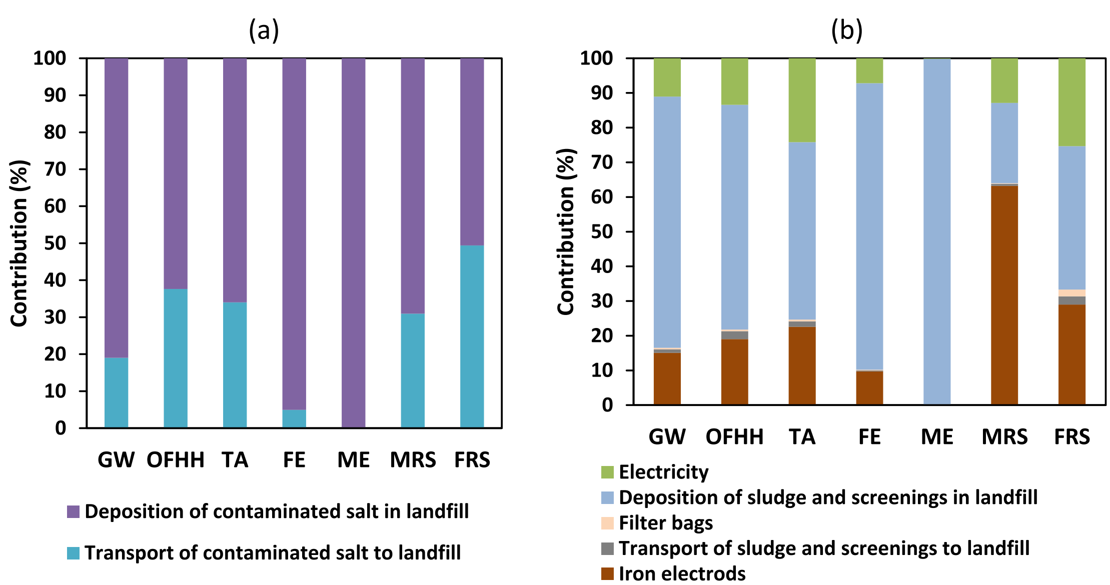

Fig. 5. Salt-derived brine: (a) contributions of disposal of the contaminated salt from the tanning industry in landfill (A_1); (b) contributions of treated contaminated salt by the electrocoagulation process (B_1).

the production and use of new iron materials.

An analysis of the environmental impacts associated with the pickling process, considering both the use of virgin salt (Scenario A) and its replacement with treated brine (Scenario B), is presented in Fig. 6. Regardless of the scenario, the use of chemicals (mainly, surfactant and formic acid, as well as sulfuric acid for TA) during the pickling process consistently emerges as the predominant contributor to environmental burdens across all assessed. Together, these chemicals account for 48% to 79% of the total impacts of this process in Scenario A, and 63% to 89% in Scenario B. Although virgin salt is the chemical consumed in the largest quantity, its contribution to the total impacts of the pickling process in Scenario A reaches 22% in MRS and 18% in FE, while remaining more moderate in the other impact categories, ranging from 2% to 8%. This explains why the reduction in environmental impacts observed in Scenario B for the pickling process reaches 29% and 25% in FE and MRS, respectively, as previously mentioned. A similar pattern is found for the remaining impact categories presented in the Supplementary Information (Figs. S4 and S5), although the contribution of virgin salt is more substantial in the ionising radiation category, accounting for 34% of the total impact.

3.2. *Codfish brine – System 2*

The results of the valorisation scenario for the treatment of codfish brine using the electro-Fenton process are presented in Table 6 and Fig. 7. When compared with the baseline, scenario B shows a substantial reduction of 88% in the FE category, along with more moderate reductions in MRS (14%), ME (6%), OFHH (3%), and TA (3%). In contrast, increases of 10% and 6% are observed for FRS and GW, respectively. For the remaining impact categories of the ReCiPe 2016 method, eight show

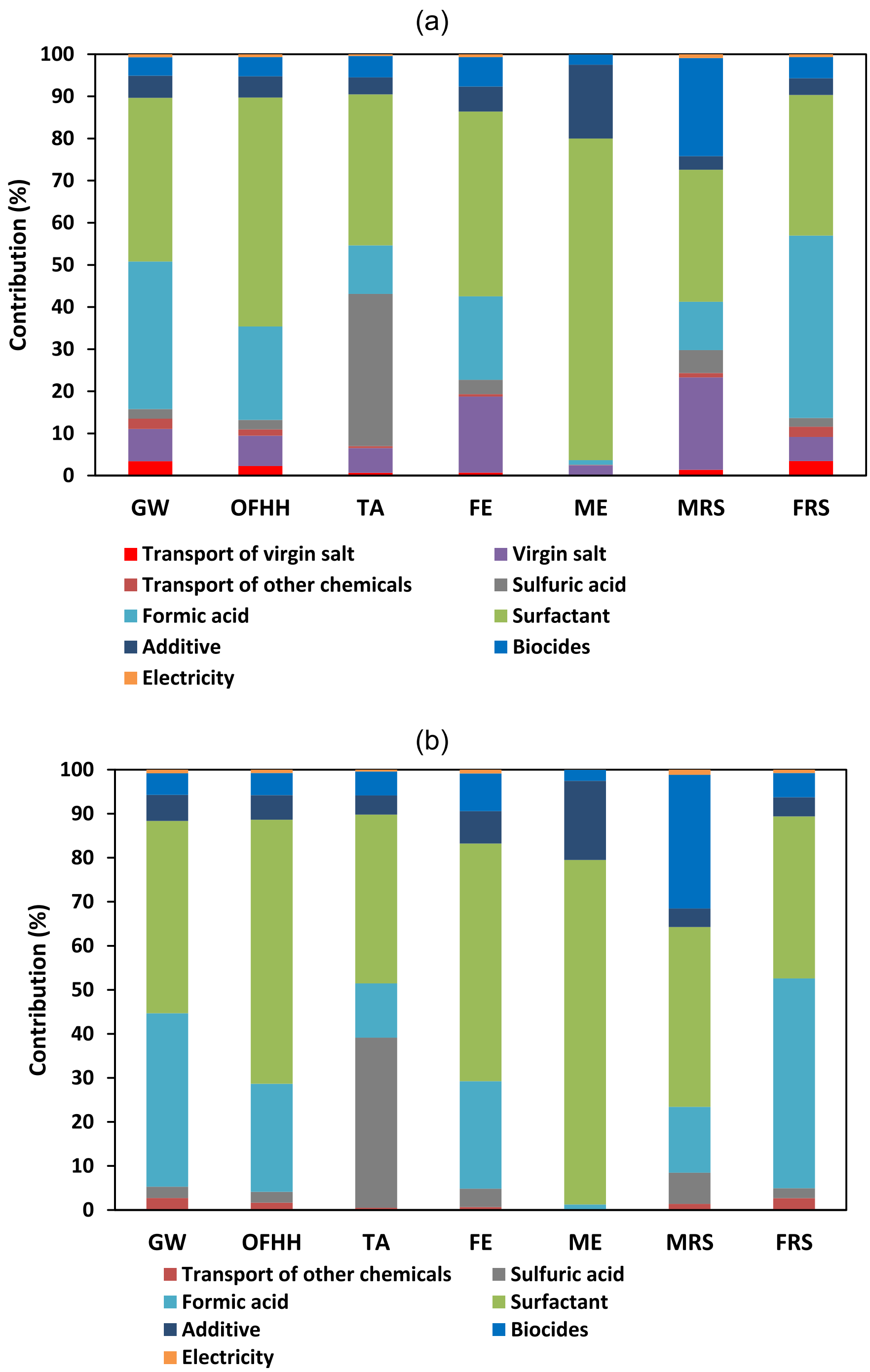

Fig. 6. Pickling process: (a) contributions of the pickling process with virgin salt (A_2), (b) contributions of pickling stage with recovered brine (B_2).

Table 6
Total impact of baseline (A) and valorisation (B) scenarios for codfish brine.

	Scenario A	Scenario B
Global warming [kg CO_2 eq]	150	159
Ozone formation, Human health [kg NO_X eq]	0.370	0.359
Terrestrial acidification [kg SO_2 eq]	1.03	1.00
Freshwater eutrophication [kg P eq]	0.464	0.0556
Marine eutrophication [kg N eq]	0.105	0.0981
Mineral resource scarcity [kg Cu eq]	0.979	0.842
Fossil resource scarcity [kg oil eq]	46.4	50.8

decreases ranging from 1% to 24%, whereas three show increases of 1% to 10%, as presented in Table S10 of the Supplementary Information.

As shown in Fig. 7, and consistent with the results presented in Fig. 4 for System 1, the pickling process remains the main contributor to environmental impacts, accounting for 90–99% across nearly all categories in both scenarios, with the exception of FE in scenario A. In this case, the treatment of contaminated brine at the WWTP plays a dominant role, contributing 87%. For the remaining impact categories presented in Fig. S6 of the Supplementary Information, the pickling process is also the primary contributor to environmental impacts. As mentioned for System 1, the impacts of the pickling process decrease by between 2% (in ME) and 23% (in MRS) in scenario B, compared with scenario A. The impacts of treating contaminated codfish brine through the electro-Fenton process also decrease by 99% and 83% in FE and ME,

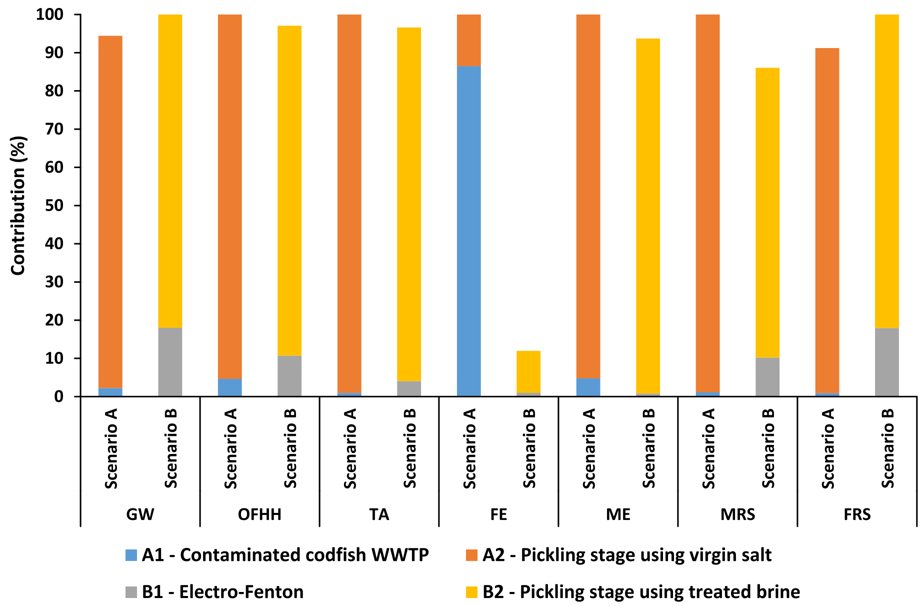

Fig. 7. Comparison between baseline (A) and valorisation (B) scenarios according to the key impact categories for codfish brine. The scenario with the greatest impact in each category is assigned a value of 100%.

respectively, when compared with the treatment at a WWTP in scenario A. However, for the remaining impact categories, the electro-Fenton process has higher environmental impacts than the treatment at a WWTP, which is more evident in GW and FRS. The results suggest that the valorisation practice proposed is an effective strategy for reducing water environmental impacts. However, it is important to carefully manage the potential increases in GW and FRS, as this could pose sustainability challenges in the long term. A similar trend of increase is observed for most of the other impact categories reported in the Supplementary Information in section S4.

The WWTP operation process is responsible for almost all the impacts (98% to nearly 100%) of Subsystem A_1 in the baseline scenario of treatment, as illustrated in Fig. 8 (a). The same pattern is obtained for the remaining impact categories presented in the Supplementary Information (Fig. S7). This indicates that the treatment process itself has a substantial environmental footprint, particularly due to high resource consumption and emissions. Specifically, GW, OFHH and TA are mainly driven by direct CO_2, SO_2 and NOx emissions to air, while FE and ME are primarily associated with phosphorus and nitrogen emissions in the treated wastewater discharged. MRS is mainly linked to iron depletion due to the use of iron chloride as a coagulant, whereas FRS is mainly caused by natural gas depletion associated with electricity consumption.

The environmental impacts associated with the electro-Fenton treatment process primarily arise from the transportation of brine between facilities and from the use of H_2O_2. Transportation is particularly relevant in the GW, OFHH, TA, MRS, and FRS categories, contributing approximately 57–66% of the total impacts, although it also plays a significant role in FE (41%) and ME (26%). The main causes of these impacts are related to direct air emissions from diesel combustion during transportation, as well as water emissions and resource consumption associated with diesel production. The use of H_2O_2 is the dominant contributor in the ME category (69%) and FE (53%) categories, while contributing 27–35% to the remaining impact categories (Fig. 8 (b)). The main drivers of the impacts associated with H_2O_2 production are

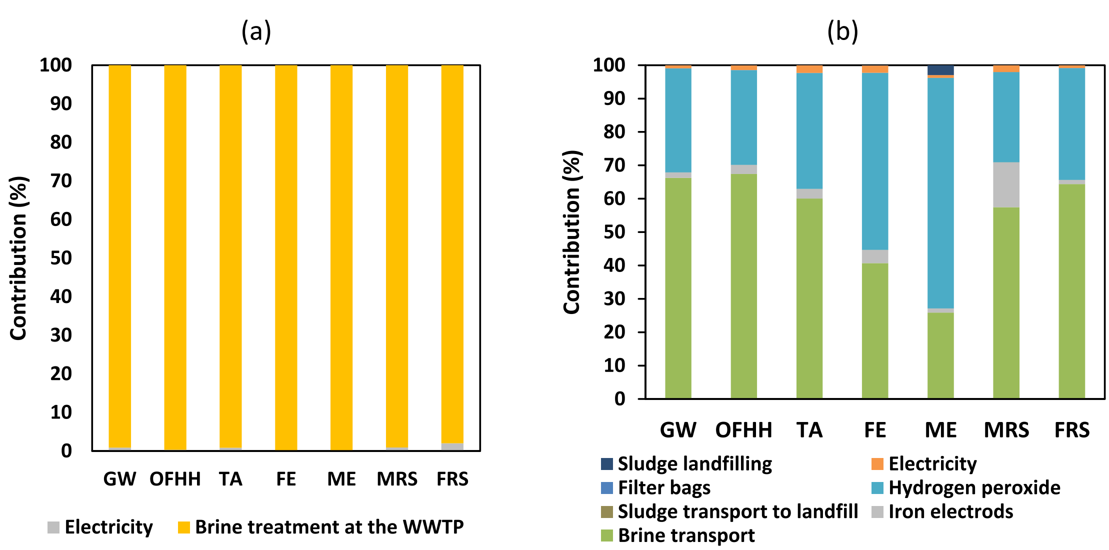

Fig. 8. Codfish brine: (a) contributions of treated contaminated brine from the codfish industry in a wastewater treatment plant (A_1); (b) contributions of treated contaminated codfish brine by electro-Fenton process (B_1).

hydrogen production (for GW, MRS and FRS), thermal energy production (for OFHH and TA), electricity production (for FE), and solid waste treatment (for ME). For the remaining impact categories presented in the Supplementary Information, the main hotspots of the electro-Fenton treatment remain the same, although iron electrodes are the largest contributor to human carcinogenic toxicity (Fig. S8). Other authors have also reported that in Fenton-based treatments, chemical inputs, particularly H_2O_2, represent the main contributors to environmental impacts (Foteinis et al., 2018; Ribeiro et al., 2024; Serra et al., 2011).

To reduce the overall environmental footprint of brine treatment by electro-Fenton, it is essential to optimise the transport of treated brine (e.g., by maximising truck load capacity and utilising trucks with low fuel consumption) and to improve the efficiency of the treatment process itself (e.g., by reducing H_2O_2 consumption).

3.3. Sensitivity analysis

A sensitivity analysis was performed for System 2 in order to evaluate how the environmental results are affected by the transportation distance between the codfish processing facility and the tanning industry, since this transport was identified as one of the main contributors to the environmental impacts of the electro-Fenton valorisation scenario. Considering that industrial symbiosis configurations may vary depending on the geographical location of the industries involved, the environmental impacts were recalculated for different transportation distances of the recovered brine. Other relevant inventory parameters for both systems, such as H_2O_2 consumption in the electro-Fenton process and chemical consumption during the pickling process, were not included in the sensitivity analysis because they were based on primary experimental and industrial data obtained under controlled operating conditions and were therefore considered to present low uncertainty.

In Scenario A (baseline), the transportation distance of the recovered brine between the codfish processing facility and the tanning industry is 110 km. In the sensitivity analysis, the environmental impacts were recalculated for shorter transportation distances to evaluate the potential environmental improvements that could be achieved if the industries involved in the industrial symbiosis strategy were located closer to each other. Fig. 9 presents the ratio between the impacts of Scenario B and those of Scenario A. A ratio below 1 indicates that the industrial symbiosis strategy is environmentally preferable to the baseline scenario. The results show that, for the GW and FRS categories, in which the impacts of Scenario B are higher than those of Scenario A for the reference distance of 110 km, Scenario B becomes environmentally favourable for transportation distances below 57 km and 27 km, respectively. For the remaining impact categories, for which Scenario B was already environmentally favourable at the reference distance of 110 km, additional environmental improvements can be achieved when the two industrial facilities are located in close proximity. Under this condition, the impacts of Scenario B may become between 6% lower for TA and 20% lower for MRS compared with Scenario A. In contrast, the FE category is only marginally affected by transportation distance.

3.4. Limitations

Several limitations should be acknowledged when interpreting the findings of this study. The life cycle inventory was developed using a combination of primary and secondary data. Primary datasets were obtained from an electrocoagulation process operated at pilot scale and from a bench-scale electro-Fenton process. While these data included information on material and energy inputs, treatment efficiencies, and emissions, they may not accurately reflect the performance of full-scale operations. Secondary data were mainly obtained from the ecoinvent v3.11 database (Wernet et al., 2016) to represent background processes. Although these datasets ensured completeness of the inventory, they may lack regional specificity and technological detail, thereby introducing additional uncertainty into the results.

Another limitation concerns the scarcity of studies in the literature addressing comparable valorisation processes for industrial saline residues, which constrained the possibility of performing a broader comparative analysis. A notable exception is the recent systematic review by Li et al. (2026) on LCA in the leather industry, which maps environmental hotspots, circular economy progress, and methodological challenges across the sector. Several findings from this review are directly relevant to and consistent with the present results.

First, the authors consistently identify wet processing stages, including pickling, as dominant contributors to environmental impacts in leather production, corroborating the finding that the pickling process accounts for 66–99% of total impacts across both systems. Second, the review highlights chemical consumption as a primary hotspot driver in tannery operations, in line with the finding that surfactants, sulfuric acid, and formic acid collectively account for 48–89% of pickling process impacts. Third, and most directly relevant to this study, Li et al.

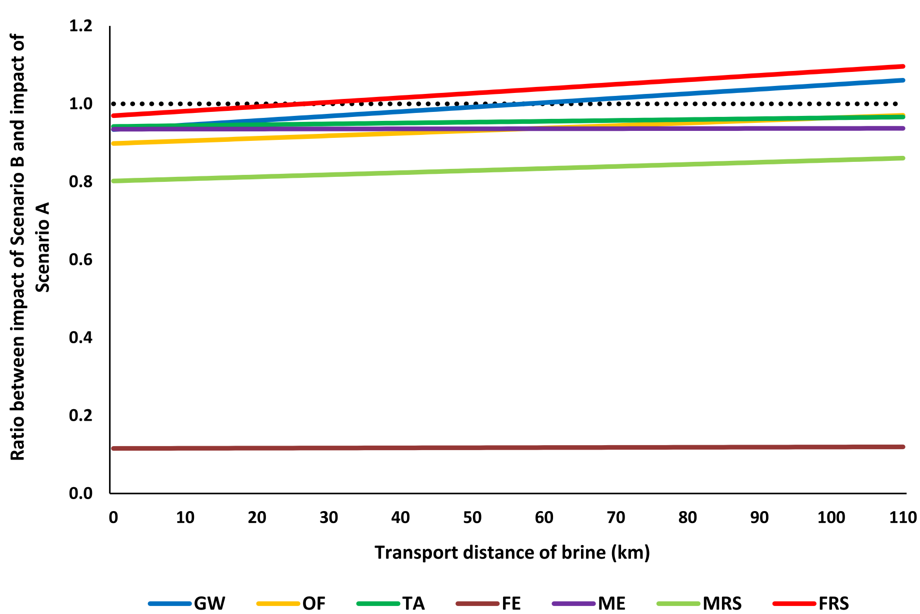

Fig. 9. Sensitivity analysis: variation of the ratio between impact of Scenario B and impact of Scenario A by changing the recovered brine transportation distance.

(2026) explicitly identify saline residue valorisation and the transition towards circular economy practices as a promising but underexplored research frontier, noting that LCA studies evaluating cross-industry resource recovery in tannery contexts remain limited.

Despite these limitations, the present study provides valuable insights into the environmental implications of saline residue valorisation, contributing original quantitative evidence to precisely this gap and offering one of the first LCA-based assessments of saline residue recovery and reuse as a viable circular economy strategy in leather processing, with particular emphasis on its potential to avoid the consumption of virgin salt.

4. Conclusions

Using the LCA methodology, this study compared conventional saline waste management practices with alternative valorisation strategies based on the recovery and reuse of treated brine within or across industrial sectors. The results demonstrated that saline residue recovery can contribute to reducing several environmental impacts associated with conventional disposal practices and virgin salt consumption, supporting the transition towards more circular and resource-efficient industrial systems.

The electrocoagulation treatment of contaminated curing salt, followed by brine reuse in the tanning industry, showed overall environmental advantages compared with the conventional practice of landfill disposal, leading to improvements across all assessed impact categories. The electro-Fenton treatment of codfish brine demonstrated the potential of industrial symbiosis strategies by enabling the reuse of saline effluents from one industrial sector as a secondary resource in another. However, this strategy presented a more mixed environmental profile. Although it resulted in improvements in several impact categories, particularly freshwater eutrophication, increases were observed in other categories, mainly due to H_2O_2 consumption and transportation requirements. These findings highlight the importance of process optimisation, particularly by acting on these key factors. The sensitivity analysis further demonstrated that the environmental performance of the industrial symbiosis strategy is strongly influenced by transportation distance, except in the ME category. The results showed that locating the industries in closer geographical proximity could significantly improve the environmental profile of the electro-Fenton valorisation scenario, making it environmentally preferable in additional impact categories. These findings highlight the importance of considering spatial planning and logistics when implementing industrial symbiosis networks based on saline residue recovery.

Although the environmental benefits associated with replacing virgin salt with treated brine in the pickling process were partially limited by the impacts of other chemicals used in this process, the proposed approaches demonstrate the potential of integrating waste recovery strategies into industrial operations as part of broader circular economy and industrial symbiosis frameworks. In particular, the reuse of treated saline effluents may contribute to reducing dependence on virgin raw materials, minimising waste disposal, and improving resource efficiency across interconnected industrial sectors. Therefore, the findings of this study may support industrial stakeholders and policymakers in the development of more sustainable waste management strategies and circular production systems, especially in industries characterised by high salt consumption and saline waste generation.

The present study was conducted based on process-specific data collected under pilot and bench-scale conditions. Future work should focus on industrial-scale validation, which is expected to result in lower environmental impacts than those obtained in this study, as well as on techno-economic assessments to further evaluate the feasibility and scalability of the proposed solutions.

CRediT authorship contribution statement

Luana Sarinho: Writing – original draft, Investigation, Conceptualization. **Mariana Pinho:** Software, Data curation. **Maria Isabel Nunes:** Writing – review & editing, Validation. **Pedro Carvalho:** Project administration, Funding acquisition. **Ana Cláudia Dias:** Writing – review & editing, Validation, Supervision, Investigation.

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.spc.2026.07.001.

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