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Socio-Environmental Assessment of a Tailings Water Softening Technology for Reuse in Alternative Systems in Central Chile: An Approach to Industrial Ecology

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Abstract

In north-central Chile, water reuse is essential due to the arid climate. Mining tailings ponds offer a promising opportunity for water recovery; however, the water quality often fails to meet the environmental standards for discharging liquid waste into marine and inland surface waters. This study proposes a bioreactor-based technology for softening tailings water while also addressing the need to quantify its sustainability impacts. To achieve that, an evaluation of the environmental and social performance of the bioreactor is conducted, comparing it with established softening methods, using an industrial ecology approach. This evaluation aims to explore scalable alternatives for sustainable water management. Environmental impacts are quantified using the ReCiPe 2016, with data sourced from Ecoinvent v3.8 and Agrifootprint databases. Social risks are assessed through the Social Hotspot Database modeling in SimaPro 9.5.0.2. The results indicate that the bioreactor demonstrates greater sustainability compared to membrane-based systems, reducing greenhouse gas emissions by more than 95%. It also registers the lowest aggregated social risks due to its minimal energy intensity, lack of hazardous chemicals, and simplified infrastructure. In contrast, reverse osmosis, while delivering higher quality permeate, results in the highest environmental burdens and occupational hazards. This research validates the bioreactor as an enabler of industrial ecology, transforming tailings water into a circular resource.

Keywords: industrial ecology; sustainability; softening water; life cycle assessment

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1. Introduction

The global water crisis disproportionately affects Chile, the world's leading copper producer, where mining operations face severe water stress [1,2]. Despite high internal water recirculation rates (73–76.3%), a prolonged megadrought, geographic constraints, and a privatized water market have intensified competition for freshwater resources, leading to social conflicts with agriculture and local communities [3–5]. Furthermore, increasing reliance on desalination creates a feedback loop, potentially exacerbating greenhouse gas emissions if not powered by renewables. This context underscores the undeniable urgency

for implementing sustainable, cross-sectoral water-management strategies in the Chilean mining industry.

Confronted with the unsustainability of the "take-make-dispose" model, which drives resource overexploitation, widespread pollution, and the worsening climate crisis, the adoption of a circular economy paradigm becomes imperative [6]. This restorative, regenerative model aims to eliminate waste and pollution while keeping products and materials in use at their highest value, thereby regenerating natural systems [7,8]. It relies on principles such as renewable energy, product-as-a-service design, extended product lifespans, and component reuse. In doing so, the circular economy not only mitigates environmental impacts but also fosters economic prosperity, job creation, and resilience for businesses and communities [9]. In resource-intensive sectors, such as mining, this transition can transform environmental liabilities into valuable assets, thereby enhancing long-term competitiveness.

Within this framework, industrial ecology operationalizes the circular economy through tools like industrial symbiosis, where waste from one process becomes a resource for another [10–12]. Applying this principle to mining, the treatment and reuse of tailings pond water emerge as a strategic solution to water scarcity in central-northern Chile. Although tailings pose environmental risks, treating this water for higher-value applications can reduce freshwater demand, decrease tailings volume, and transform an environmental liability into an operational resource [13–15].

Furthermore, the chemical complexity of tailings storage facility (TSF) waters in Chile extends beyond conventional pollutants. While copper mining is a dominant activity, the associated ore bodies often contain significant concentrations of toxic heavy metals and metalloids, such as arsenic, cadmium, lead, and zinc, which readily leach into process water. Only then can the mining sector truly close its water loop, ensuring environmental protection and long-term sustainability. To tackle the high ionic load of tailings pond water, various advanced softening and purification technologies are employed, often in multistage systems designed to maximize water recovery and minimize waste, sometimes even achieving zero discharge [16]. Among them, reverse osmosis (RO) and nanofiltration (NF) are pressure-driven, membrane-based methods, with RO being more thorough but energy-intensive [17–19]. In contrast, ion exchange (IX) uses polymer resins to swap specific ions [20].

Beyond conventional physicochemical methods, biological treatments using bioreactors are emerging as sustainable solutions for mine waters rich in sulfates and metals [21,22]. The treatment relies on the activity of sulfate-reducing bacteria (SRB) under anaerobic conditions. These bacteria utilize organic matter as an electron donor to reduce sulfate, generating sulfide that precipitates dissolved metals as highly insoluble metal sulfides, thereby achieving significant contaminant removal [23,24]. The key advantages of bioreactors are their lower operational costs, reduced sludge production, and potential for valuable metal recovery, aligning with circular economy principles [25,26]. However, their effectiveness depends on carefully controlling parameters like pH and metal concentration due to microbial sensitivity [27,28].

Given the complexity of water management in mining, the multifaceted challenges of northern and central Chile, and the emergence of advanced treatments such as bioreactors, an exhaustive impact assessment is essential. This evaluation must extend beyond technical performance to encompass the full spectrum of socio-environmental implications [29,30]. Life Cycle Assessment (LCA) provides a robust framework for this integrated analysis, systematically quantifying impacts from raw-material extraction through disposal [31,32]. A genuinely holistic assessment combines Social LCA (S-LCA), which examines human rights, labor conditions, health and safety, and broader socio-economic consequences [33–36], with Environmental LCA (E-LCA), which measures potential impacts such as climate change,

acidification, ecotoxicity, mineral and fossil resource depletion, eutrophication, human toxicity and other impacts [37,38]. By applying a combined S-LCA and E-LCA approach, this study aims to deliver a comprehensive understanding of the environmental footprint and social ramifications of implementing tailings-water softening technologies, with a focus on bioreactors for reuse in alternative systems in northern and central Chile. Such an integrated evaluation is vital for informed decision making, ensuring that technological solutions genuinely advance sustainable development and secure the social license to operate for mining activities.

2. Materials and Methods

2.1. Bioreactor Technology & Experimental Setup

Bioreactors are used for the passive treatment of mining wastewater [27,39] and are based on the anaerobic metabolism of bacteria that decompose organic matter using SO_4^{2-} (sulfates) as electron acceptor and the reduced to S^{2-} (sulfides), a species that forms stable compounds with metals, of zero or low solubility. This process of sulfate reduction and precipitation of metals in the form of sulfides occurs naturally in wetlands [40]. Sulfate-reducing bacteria (SRB) are strict anaerobes belonging to genera such as Desulfovibrio and Desulfotomaculum, as well as facultative anaerobic bacteria, of genera such as Vibrio and Citrobacter [41]. Bioreactors are versatile and can adapt to the required operating conditions, and they are available in various configurations, including vertical and horizontal designs, made of different materials and dimensions [42]. A key factor in bioreactors is the mixture of different types of organic materials, which can be processed quickly or slowly, thereby regulating the activity of sulfate-reducing bacteria.

In an assay using mining wastewater from the Ovejería TSF, characterized by Mo and SO_4^{2-} concentrations exceeding the limits established by the Chilean regulation for contaminants associated with the discharge of liquid wastes to marine and continental surface waters [43,44], the performance of different substrate mixtures was evaluated. The core substrate, comprising pine needles and corn stover as slow-release carbon sources, bovine manure as the inoculum for SRB, steel slag as an electron donor and precipitation agent, and gravel as a structural matrix, was amended with different plant-based organic substrates. This combination of materials was designed to create a synergistic environment that supports SRB metabolism, thereby directly facilitating the bacterial reduction in sulfate.

The experimental setup consisted of down-flow vertical bioreactors with a 15 L working volume, equipped with upper and lower valves for influent (initial clarifier water) and effluent (post-treatment water) management, respectively. Each bioreactor featured a stainless-steel mechanical agitator chosen for its low carbon content and high corrosion resistance against SRB. The substrate bed included a mixture of organic and inorganic materials layered over a gravel base enclosed in Raschel mesh. Systems remained hermetically sealed throughout a 120-day experimental period, with weekly 30-s agitation cycles using a 12V wireless drill to maintain homogenization. Physicochemical parameters (pH, EC, DO, ORP, TDS, and temperature) were measured weekly with a HANNA HI7698194 multiparameter probe inserted through a dedicated upper port. Simultaneously, ambient conditions were continuously recorded using a VETO RC-4HC data logger. Effluent samples were collected biweekly from the lower valve for sulfate and molybdenum analysis via turbidimetry and ICP-OES, respectively. This design ensured static operational conditions without continuous flow, focusing on evaluating treatment capacity under extended batch regimes [45].

The superior reduction in Mo and SO_4^{2-} was achieved with the addition of *Carpobrotus chilensis* remains compared to *Opuntia ficus-indica* (Table 1). This enhanced performance is attributed to the more effective role of *Carpobrotus chilensis* as a complementary organic

substrate, which likely provided a more readily available carbon source to sustain and stimulate the metabolic activity of the SRB, thereby driving the reductive and precipitation processes more. The initial mining wastewater concentration, 2295 mg/L of SO_4^{2-}, decreased to 308 mg/L after 75 days, while Mo decreased to less than the detection limit (<dl), complying with the standard for discharge into surface waters. After 120 days, both treatments, *Carpobrotus chilensis* and *Opuntia ficus indica*, met water quality regulations for irrigation and discharge into surface waters [45]. However, a higher pH value of the treated water is more suitable.

Table 1. Chemical parameters of mining wastewater treated by biorreactors with different substrates and comparison with Chilean regulations [45].

Days	Properties	Control (Only Mining Wastewater)	Substrates with *Carpobrotus chilensis*	Substrates with *Opuntia ficus indica*	Chilean Regulation	
					NCh 1333	D90
Initial	pH	7.9	7.9	7.9	5.5–9.0	6.0–8.5
	Electrical conductivity (mS/cm)	2.93	2.93	2.93	0.75–7.5	-
	Mo (mg/L)	1.37 ± 0.04	1.37 ± 0.04	1.37 ± 0.04	0.01	1.00
	SO_4^{2-} (mg/L)	2295 ± 285	2295 ± 285	2295 ± 285	250	1000
75	pH	7.2 ± 0.4	6.5 ± 0.06	5.6 ± 0.4	5.5–9.0	6.0–8.5
	Electrical conductivity (mS/cm)	2.94 ± 0.04	10.8 ± 0.17	6.92 ± 0.25	0.75–7.5	-
	Mo (mg/L)	0.93 ± 0.06	<dl	<dl	0.01	1.00
	SO_4^{2-} (mg/L)	1670 ± 60.4	308 ± 38.1	647 ± 286	250	1000
120	pH	7.4 ± 0.23	6.9 ± 0.08	6.4 ± 0.73	5.5–9.0	6.0–8.5
	Electrical conductivity (mS/cm)	3.12 ± 0.15	10.6 ± 0.65	7.93 ± 0.41	0.75–7.5	-
	Mo (mg/L)	0.97 ± 0.05	<dl	<dl	0.01	1.00
	SO_4^{2-} (mg/L)	1702 ± 15.5	70.1 ± 30.5	70.4 ± 17.7	250	1000

A relevant aspect is that the organic matter from the residual substrates of the bioreactors completes its cycle through composting, generating an organic amendment for use in the phytostabilization of mining tailings. The mining wastewater treated in the bioreactors complies with the standard for the regulation of pollutants associated with the discharge of liquid waste into marine and inland surface waters (D90) [46], for discharge into the Chacabuco estuary, located near the tailings dam, which will help alleviate water stress in the area and contribute to sustainable mining practices.

The quality of organic matter, in this case, the configuration with Carpobrotus chilensis (Doca), had a significant effect on decreasing SO_4^{2-} in the water, indicating an interesting line of work in evaluating different agricultural residues for these purposes. Using organic waste in a bioreactor to treat mining water and produce compost from the residual substrates of the bioreactor for the phytostabilization of mining tailings land creates a valuable connection between sectors that compete for land use, such as agriculture and mining, to promote industrial ecology [47]. An interesting management plan would be to treat a portion of the mining wastewater through passive bioreactor treatment. Treated water, suitable according to D90 for discharge into rivers, estuaries, and wetlands adjacent to mining activities, contributes to reducing the company's water footprint and reducing the social and environmental pressure exerted by communities (Figure 1).

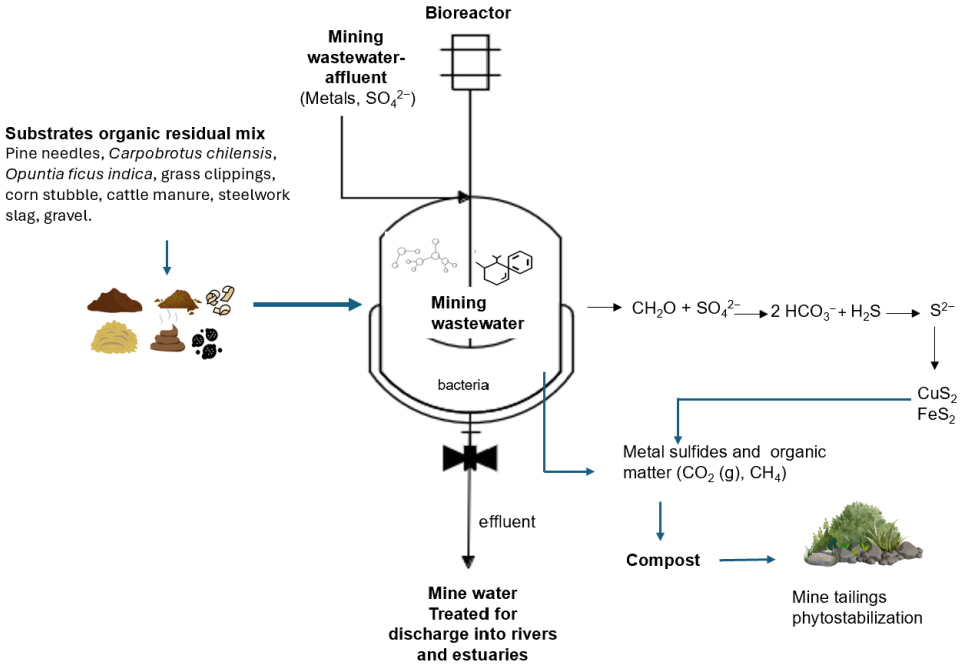

Figure 1. Process flow of a passive bioreactor for mining wastewater treatment: Inputs, biochemical pathways, and valorizable outputs.

2.2. Life Cycle Assessment Methodology

The LCA is a standardized, comprehensive method used to evaluate the environmental, social, and economic impacts of a product, process, or service throughout its entire life cycle, from raw material extraction and manufacturing to use and final disposal or recycling. Following international standards like ISO 14040 and the ILCD Handbook [29], LCA involves creating an inventory of relevant system inputs and outputs while assessing their effects on ecosystems, human health, and resource availability. An essential part of LCA is modeling how individual life cycle processes and impact categories are connected through specific indicators, enabling a detailed analysis of each process's role in overall sustainability. This unified approach enables organizations and policymakers to identify key sustainability issues, make data-driven decisions, and develop strategies that improve circularity, mitigate negative impacts, and support sustainable development over time. According to ISO 14040 [37], an LCA study has four main phases, with each phase influencing the others (Figure 2).

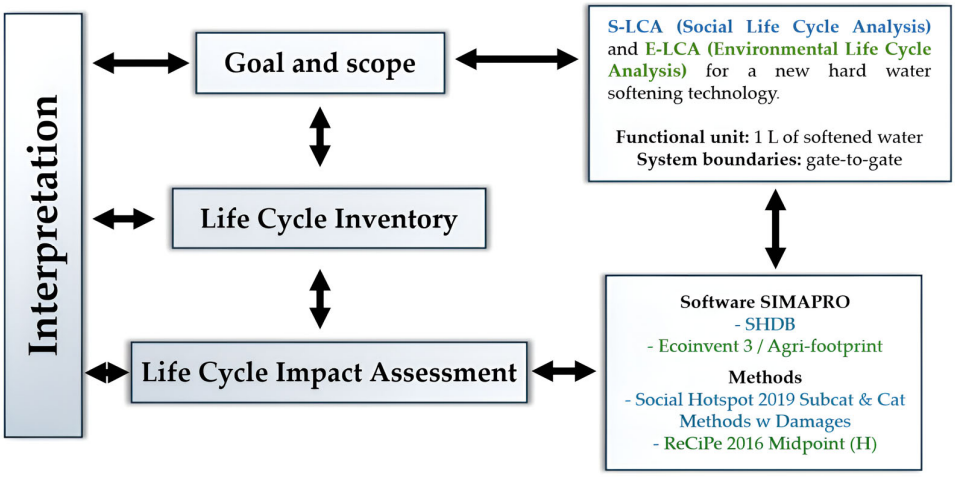

Figure 2. Life Cycle Assessment Structure [37].

2.2.1. Goal and Scope Definition

Objective: Conduct a gate-to-gate environmental and social LCA of a bioreactor-based water softening process.

Function: To soften tailings water via a biologically driven sulfate-reducing mechanism.

Functional Unit: 1 l of softened tailings water at the treatment plant outlet.

System Boundaries:

Water pre-conditioning.

Bioreactor operation (inoculation, nutrient dosing, mixing, aeration, carrier regeneration).

Spent regenerant management.

Upstream impacts of inoculum, nutrients, and carrier manufacture.

2.2.2. Life Cycle Inventory

Data Sources: A combination of primary data from pilot-scale experiments and secondary data from established databases (Ecoinvent 3, AgriFootprint).

Foreground System: Empirical data on water flow rates, nutrient doses, biomass yield, and carrier mass turnover (Tables 2 and 3).

Table 2. Physical characteristics of the substrates employed [45].

Substrate	Density (g/L)	Mg/m^3	Moisture (%)
Pine needles	79.2	0.08	-
Carpobrotus chilensis (Doca)	554.3	0.55	92
Corn stover	26.7	0.03	-
Bovine manure	728.0	0.73	78
Steel slag	1822.4	1.82	-
Gravel	1272.0	1.27	-

Table 3. Proportions of raw materials utilized in each treatment.

Substrate	Value (kg/L)	Cost USD/kg	Value/USD	SDHB Sector	Source
Pine needles	0.007	1.83	0.01281	pbf	Chile
Carpobrotus chilensis (Doca)	0.111	-	-	ocr	Chile
Corn stover	0.003	1.81	0.00468	gro	Chile
Bovine manure	0.002	0.46	0.00085	ctl	Chile
Steel slag	0.019	0.01	0.00022	i_s	Chile
Gravel	0.180	0.34	0.06048	nmm	Chile

Background System: Embodied impacts of materials, energy, and components modeled using geographic/technological proxies for Chile.

Social Data: Social risk profiles obtained from the Social Hotspots Database (SHDB) using a spend-based assessment approach [48,49].

Comparative Analysis: Inventory data for alternative technologies (Reverse Osmosis, Nanofiltration, Ion Exchange (Anion exchange resins columns)) were also compiled for a harmonized comparative assessment. These comprehensive data are provided in the Supplementary Materials.

Note: Carpobrotus chilensis (Doca) has no market price and is excluded from the spend-based social assessment (Table 3).

2.2.3. Life Cycle Impact Assessment

Software: SimaPro.

Environmental Methodology: ReCiPe 2016 (Hierarchist perspective), evaluating both midpoint and endpoint (community) impact categories.

Social Methodology: Social Hotspot Database 2019 method, quantifying social risks and damages across the supply chain.

Procedure: Inventory data was characterized, normalized, and weighted according to the chosen methodologies to generate a comprehensive profile of environmental and social impacts.

3. Results

3.1. Social Life Cycle Assessment

In Figure 3, a Pareto analysis was conducted to identify the social impact categories contributing the most to the cumulative impact, following the 80/20 principle. The figure caption describes a graph where the left Y-axis indicates the Impact Score, representing the quantified social risk in dimensionless points as per the SHDB methodology, while the right Y-axis displays the Cumulative Percentage of the total impact, in case of the X-axis, which represents the different impact categories whose distinct dimensions used in S-LCA to evaluate human rights, labor conditions, and broader socio-economic consequences. The bars depict the individual impact score for each social category, and a red line illustrates the cumulative percentage, with the point at which it crosses the 80% threshold emphasizing the most critical categories.

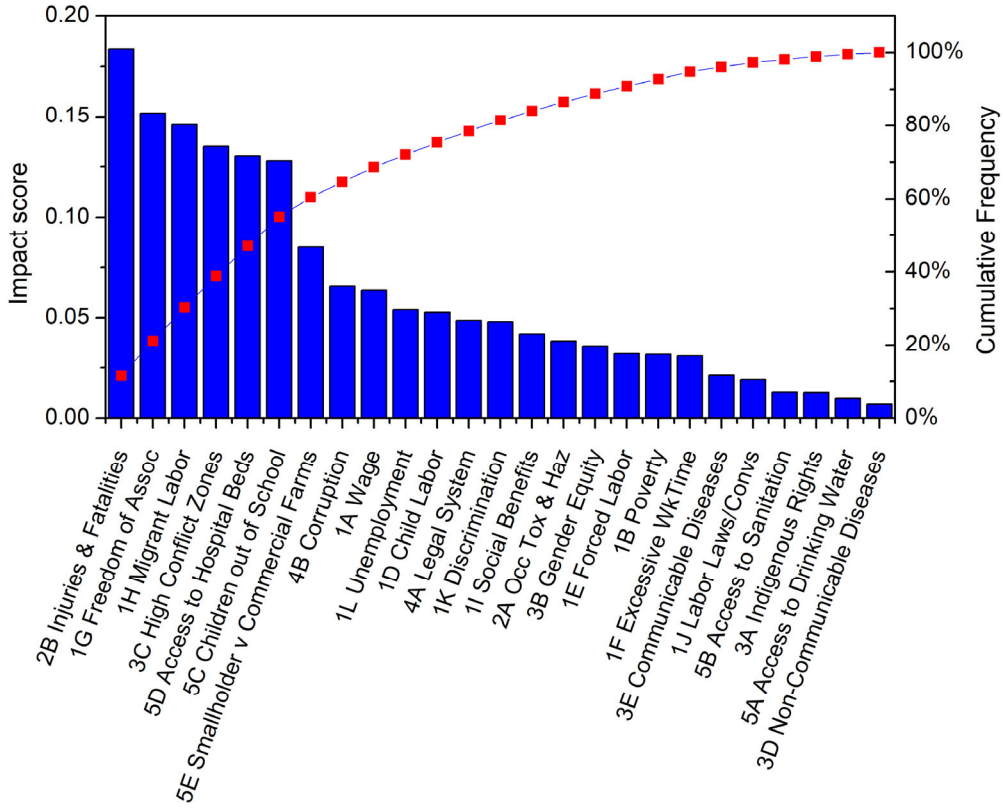

Figure 3. Weighted Pareto Analysis: Cumulative Percentage Impact Score of Social Impact Categories in Passive Bioreactor Systems made with SimaPro.

Focusing on risk mitigation for the "Injuries & Fatalities" category, identified as the main contributor to social impact in Figure 3, allows for targeted and efficient reduction in the bioreactor's overall social footprint. Using a network analysis in SimaPro with the

SHDB's spend-based assessment methodology and a 4% cut-off threshold, the specific components and processes within the system that generate this impact were identified. Figure 4 refers to the upstream economic activities and sectors involved in producing and supplying the raw materials that make up the bioreactor's substrate mixture. This precision enables strategic interventions, such as enhancing safety protocols, improving supplier engagement, or implementing technical modifications, directly at the most influential points, thereby maximizing the effectiveness of mitigation efforts and significantly reducing the total social impact.

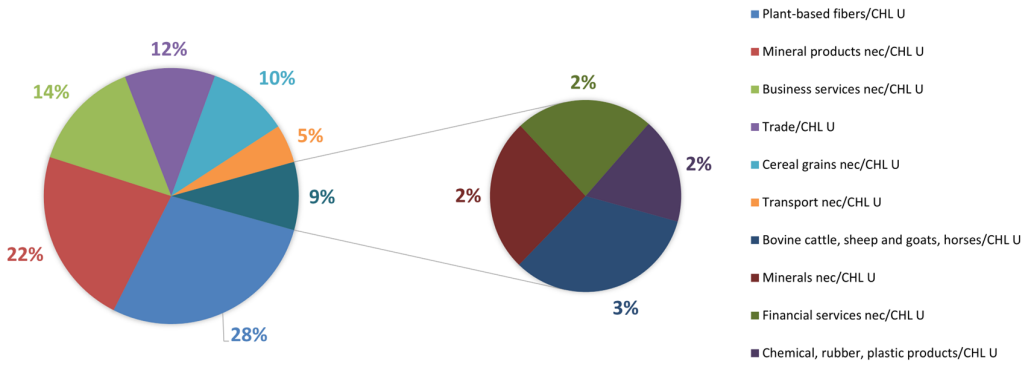

Figure 4. Percentage contribution of bioreactor components supply chain to "Injury/Fatalities" social impact category.

As shown in Figure 4, "plant-based fibers" (pine needles) emerge as the leading contributor, accounting for approximately 28% of the total impact, followed by "mineral products nec" (gravel used in the system's technology), which accounts for 22%. This outcome is linked to the forestry and mining sectors in Chile, both of which are characterized by high-risk working conditions. In the forestry industry, workers face physically demanding tasks, hazardous machinery, and an increasing threat of wildfires, reflecting deficiencies in training and safety measures. In mining, drilling, blasting, and material handling activities also pose a high risk of accidents, exacerbated by insufficient safety standards. The high incidence of injuries and fatalities in both sectors reveals structural shortcomings in labor protection and enforcement.

To mitigate these risks, a combination of stringent policy interventions and proactive corporate practices is essential. Policy measures should focus on strengthening and rigorously enforcing safety regulations, including the mandatory use of personal protective equipment and modern operational protocols, complemented by a system of frequent, unannounced independent audits and the integration of strict social criteria into public procurement to reward verified safe practices. Concurrently, corporate actions must involve investing in a proactive safety culture through comprehensive, hands-on training, adopting technological solutions to mechanize the most hazardous tasks, and establishing worker empowerment programs that include anonymous reporting channels to ensure direct employee involvement in safety monitoring. Therefore, it becomes necessary to conduct an LCIA to evaluate the contribution of each component to the different impact categories (Figure 5).

Figure 5 presents a comprehensive view of the distribution of bioreactor technology components across various impact categories. By quantifying the contributions of each component to the overall social impact of technology, this analysis provides critical insights for researchers and practitioners. It enables the precise identification of key elements that disproportionately influence social outcomes, thereby informing targeted improvements to optimize performance and align the system with societal expectations. The different social impact categories are the subjects of assessment. The chart displays the calculated

impact score for the entire bioreactor system, categorized by each of these areas. The connection is that the life cycle inventory of the bioreactor's inputs is assessed against each of these pre-defined social impact categories using the SHDB's characterization factors. Notably, two components, mineral products nec, representing gravel, and plant-based fibers, associated with pine needles, consistently emerge as the most influential across all assessed impact categories. This dual prominence highlights the need to prioritize both the extraction and supply chains of these materials for further examination and improvement. Addressing the occupational risks associated with mining and forestry operations is crucial for mitigating the broader social impacts inherent in the bioreactor system. Building on this foundation, the study compares the bioreactor system to alternative water softening technologies, paving the way for the results shown in Figure 6.

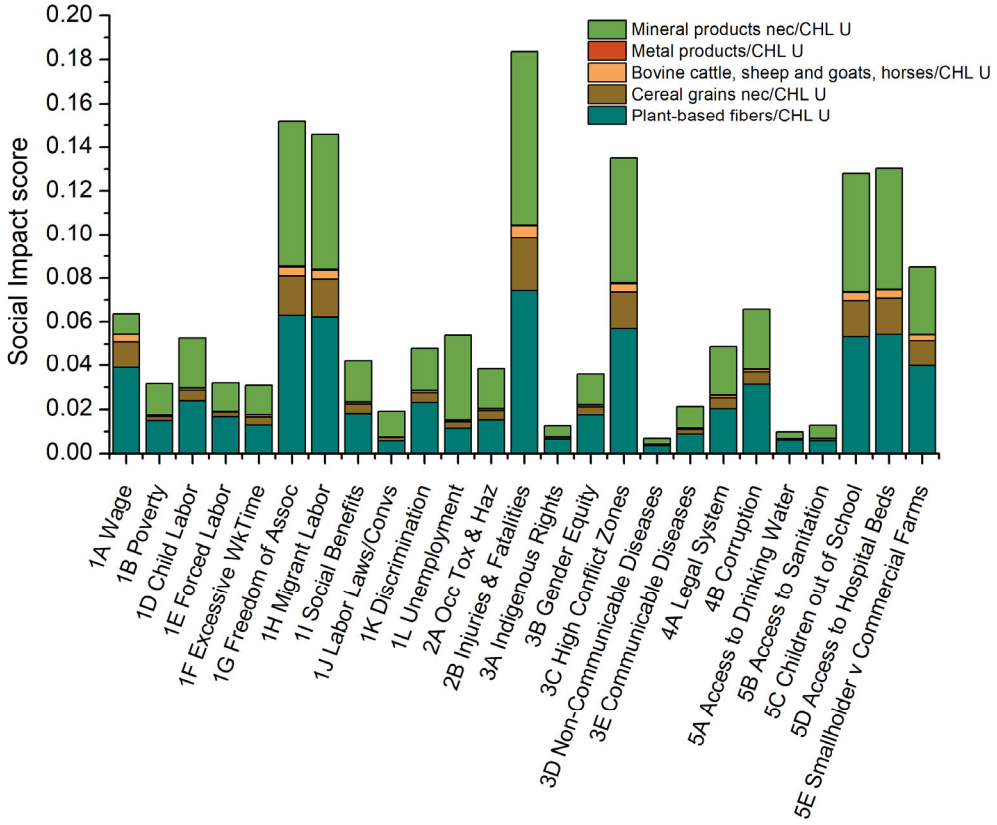

Figure 5. Social Life Cycle Impact Assessment of the Bioreactor Technology.

The comparative analysis of water treatment technologies highlights a consistent pattern in the distribution of social impacts (Figure 6). The bioreactor stands out as the option with the lowest social burden across the evaluated categories, making it the most socially sustainable choice. In contrast, RO has the highest social impacts, followed by NF, which illustrates a clear trend: membrane-based technologies tend to have greater social impacts. This is primarily due to their higher energy demands and reliance on specialized materials and components, often sourced from supply chains characterized by poor labor conditions, limited wage equity, and increased occupational risks. Additionally, the IX shows slightly lower impacts than NF but still has higher impacts than bioreactors. This gradient emphasizes the importance of evaluating both technical performance and the social dimensions associated with each technological alternative.

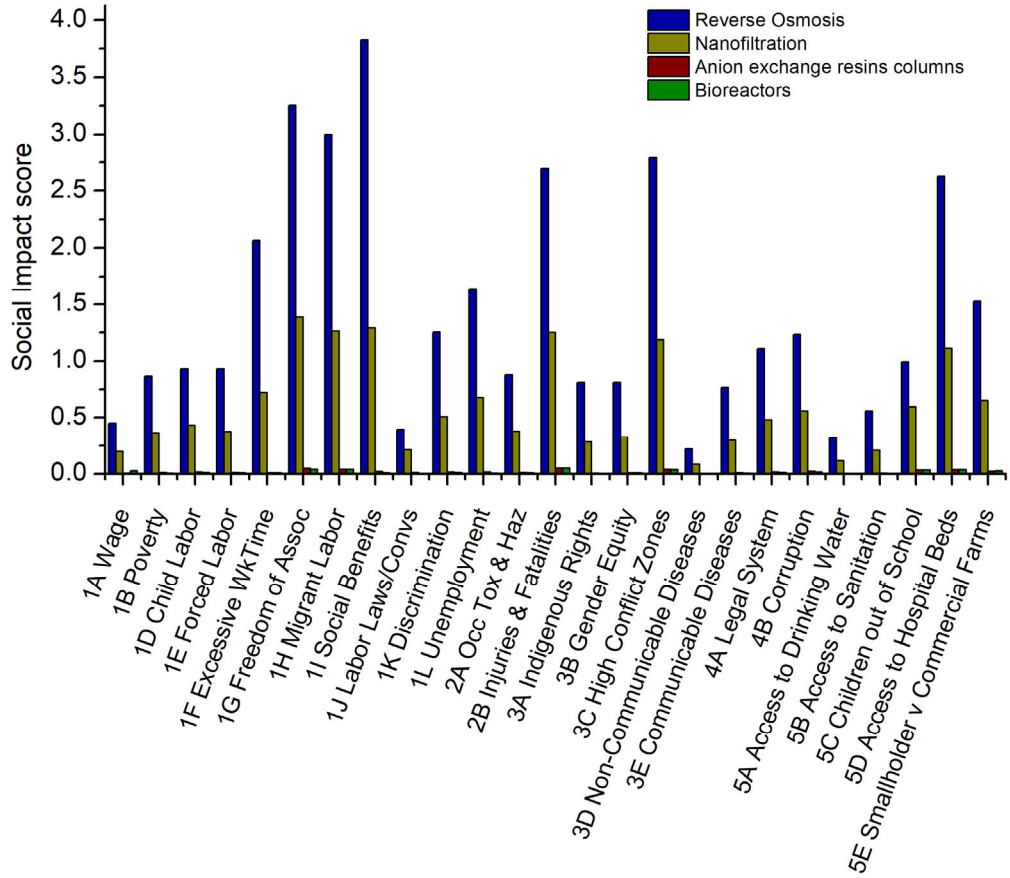

Figure 6. Comparative Social Life Cycle Impact Assessment of four water-softening technologies.

Specifically, in the overall Community Endpoint category, the bioreactor has the least reduced impact, indicating a smaller contribution to the community risks, with a value of 1.13×10^{-7} pts. Conversely, RO registers the highest impact in this metric, indicating a greater social burden at the community level. At the same time, NF and IX fall within an intermediate range (Figure 7).

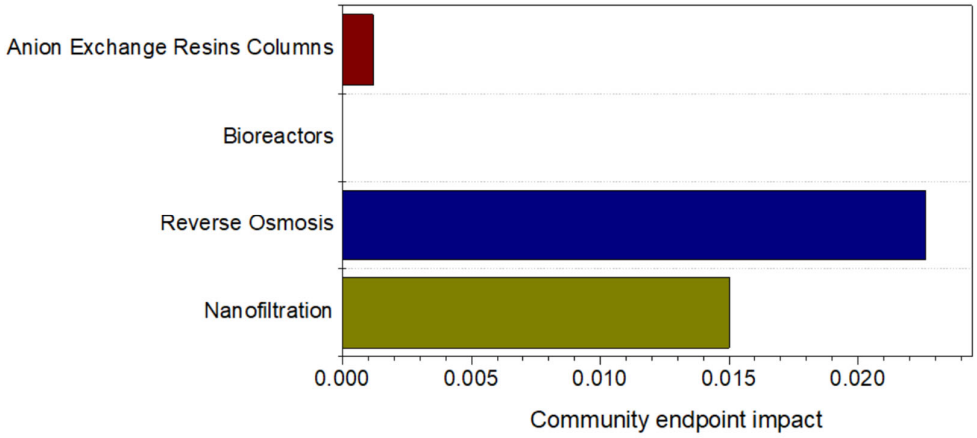

Figure 7. Community-endpoint Social Impact comparison for the four softening water technologies.

3.2. Environmental Life Cycle Assessment

Figure 8 displays a Pareto chart, which highlights the most impactful factors in a dataset, in line with the 80/20 principle. Where the right Y-axis displays the Cumulative Percentage of the total impact. The bars depict the individual impact score for each

environmental category, and a red line illustrates the cumulative percentage, with the point at which it crosses the 80% threshold emphasizing the most critical categories.

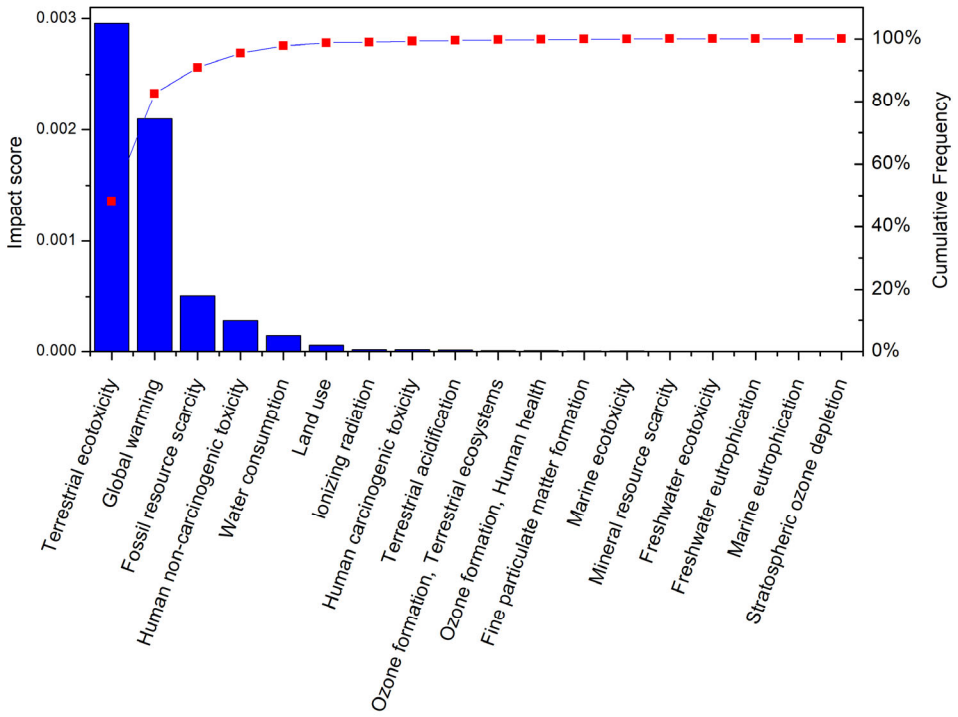

Figure 8. Weighted Pareto Analysis: Cumulative Percentage Contribution of Environmental Impact Categories in Passive Bioreactor Systems.

In the figure, among all environmental impact categories, Terrestrial Ecotoxicity stands out as the most significant contributor to the bioreactor's footprint. Its predominant influence suggests that addressing this specific category, through cleaner raw materials or more efficient emissions control, could lead to a meaningful reduction in the overall environmental impact of the system, making it necessary to identify which components or supply-chain stages contribute most to this impact category (Figure 9).

In the analysis of contributions to the Human Carcinogenic Toxicity impact category, a cut-off threshold of 3.5% reveals that granulated blast furnace slag is the predominant contributor, accounting for 59.4% of the total impact. Following this, crushed gravel is identified as the second major contributor, accounting for 32.7% of the impact, which could be attributed to their production chains. For crushed gravel, the impact is primarily linked to soil emissions from the diesel-powered machinery used for extraction and crushing. In the case of granulated slag, the impact can be attributed to the burden allocation of emissions from the industrial steelmaking process, from which it is a co-product, particularly concerning heavy metals contained in the material. This can be seen in the other notable contributors, including solid cattle manure at 5.1%, low-alloyed hot-rolled steel at 3.5%, and the diesel used in construction machinery, which contributes 7.8%. Additionally, the medium voltage electricity supply contributes 8.0% and 7.0%, varying by the regional electricity mix. These results suggest that mineral-based materials and energy sources play a significant role in driving human carcinogenic toxicity. Therefore, implementing targeted strategies to replace key raw materials and enhance energy efficiency could be an effective way to reduce potential health risks related to the technology, which requires conducting a detailed LCIA of the technology in this specific case (Figure 10).

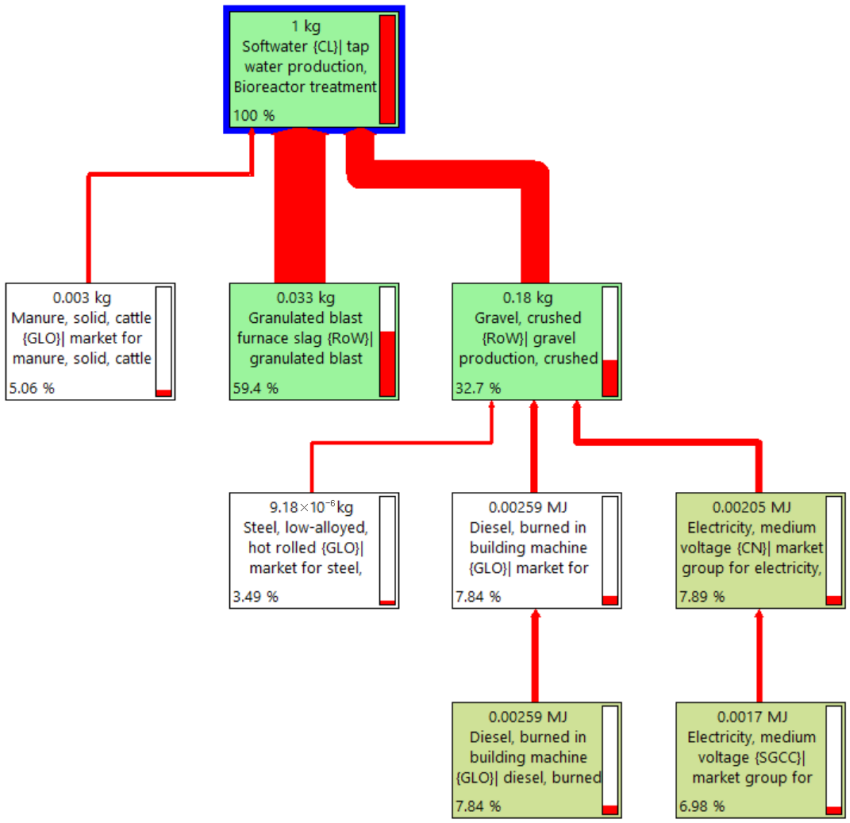

Figure 9. "Human Carcinogenic Toxicity" causal network in Bioreactor Technology.

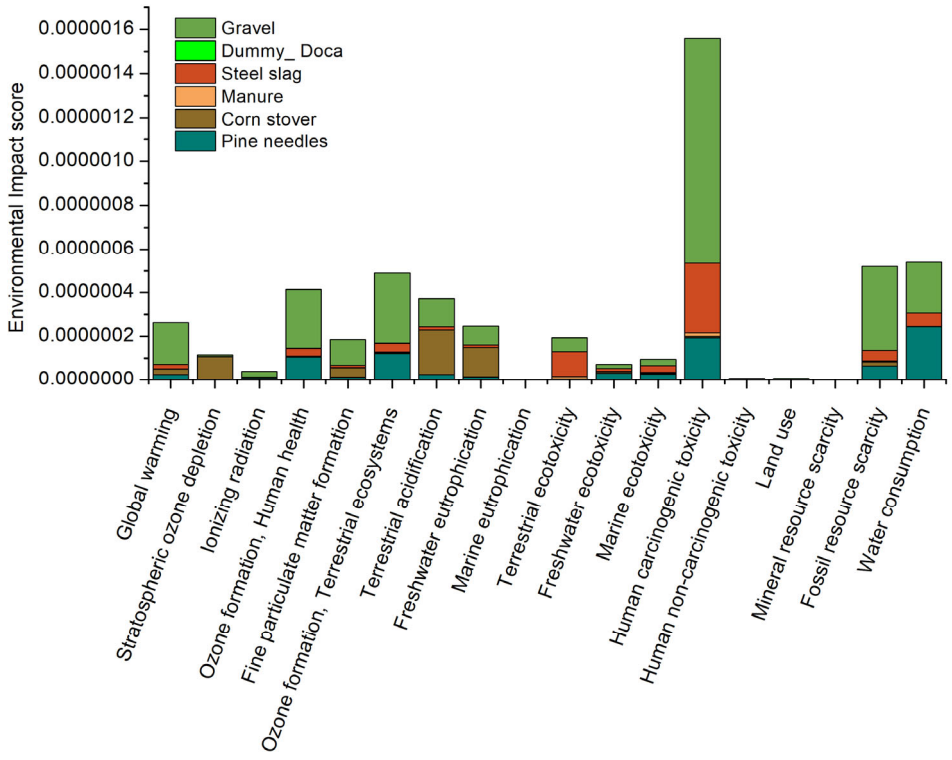

Figure 10. Environmental Life Cycle Impact Assessment of the Bioreactor technology.

Figure 10 illustrates the analysis of the environmental impact distribution of bioreactor components, which reveals that mineral-derived inputs, particularly gravel, have the most significant influence on climate-related and resource use categories, including Global Warming, Ozone Formation for Human Health, Terrestrial Ecosystems, and Water

Consumption. This underscores the high energy and material demands associated with the extraction and processing of aggregates. Corn stover has the highest relative impact on Terrestrial acidification, Freshwater eutrophication, and Stratospheric Ozone Depletion. This is likely due to the use of nitrogenous fertilizers, pesticides, and herbicides in maize cultivation. The metrics for Ecotoxicity, specifically Terrestrial Ecotoxicity, Freshwater Ecotoxicity, and Marine Ecotoxicity, exhibit a more varied profile, with significant contributions from pine needles, steel slag, and bovine manure. Meanwhile, Human Carcinogenic Toxicity is primarily driven by substances such as gravel, steel slag, and pine needles. It is essential to note that gravel also plays a significant role, highlighting the substantial impact of metallurgical by-products and lignocellulosic residues on toxicological pathways. Following the component-level LCIA, the focus shifts to a comparative assessment of four water-softening technologies (Figure 11).

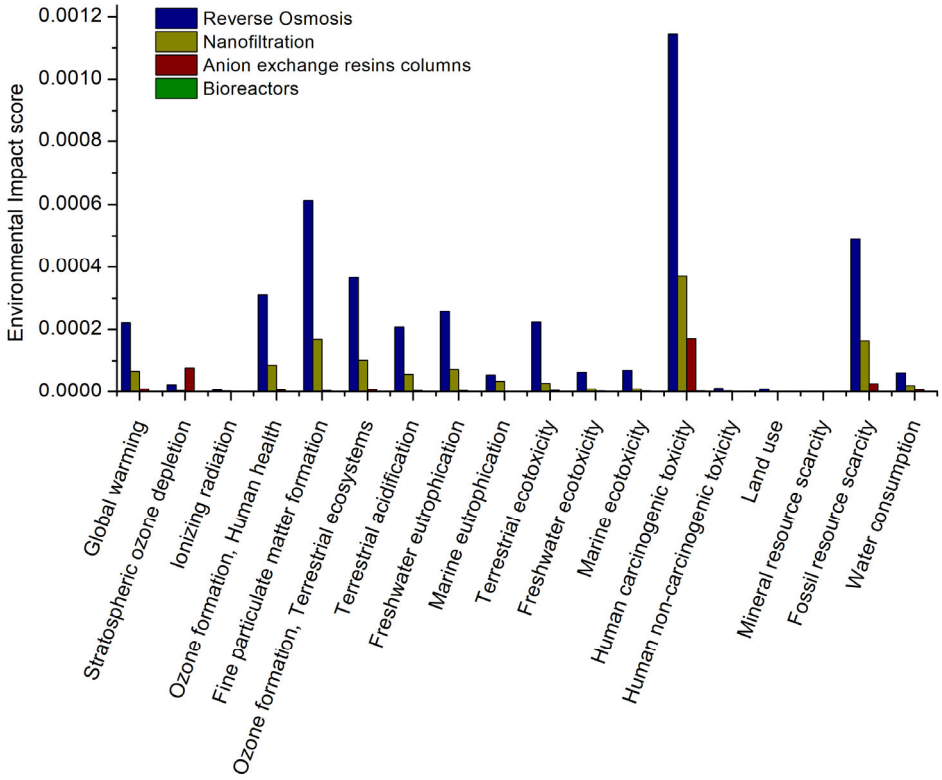

Figure 11. Comparative Environmental Life Cycle Impact Assessment of four water-softening technologies.

Figure 11 shows a comparative LCIA of four water softening technologies, indicating that RO imposes the highest environmental burdens across nearly all indicators: Global Warming, Ozone Formation Affecting Human Health and Terrestrial Ecosystems, Fine Particulate Matter Formation, Terrestrial Acidification, Freshwater Eutrophication, and Human Carcinogenic Toxicity due to its substantial energy and material demands. NF exhibits a similar impact profile but at markedly lower magnitudes. In contrast, IX drastically reduces climate-related emissions and resource use, albeit with moderate contributions to eutrophication and water consumption due to nutrient requirements and operational losses. Finally, bioreactor technology records the lowest normalized impacts in every category, reflecting negligible energy and material inputs. These findings highlight the trade-offs between energy-intensive membrane processes and biological solutions, underscoring the importance of aligning technology selection with the specific environmental priorities of each application.

4. Discussion

From a discussion perspective, it is essential to acknowledge that energy costs and water consumption represent critical economic factors in mining processes. In this context, conventional technologies such as RO, though necessary due to water scarcity and time constraints, entail high energy consumption and generate waste, such as brines, whose management in settings like Chile remains environmentally uncertain. Water scarcity not only limits production but also affects vulnerable aquatic ecosystems in the arid and semi-arid regions where mining operations are located. Therefore, the treatment of mining wastewater should transcend a production-centric approach and strive to recharge surrounding water bodies, such as estuaries, rivers, or wetlands.

In this scenario, bioreactors emerge as a promising alternative for the passive treatment of water from tailings dams, contributing to the circular economy through multiple pathways: the use of agricultural waste as substrate, the recharge of surface watercourses with treated water, the utilization of organic waste from bioreactors as compost for phytoremediation of the TSF, and the maintenance of tailings storage stability through passive processes that avoid aggressive water extraction.

The pilot-scale results demonstrate the bioreactor's efficacy in removing molybdenum and sulfate, while its passive batch operation ensures tailings dam stability by avoiding rapid water extraction. This positions the technology as a promising solution for water reuse in tailings storage facilities, particularly in water-scarce regions of north-central Chile. To implement these findings, mining companies should initiate scaling using the supportive lab and LCA data. Regulators ought to develop frameworks that incentivize such passive treatment systems. Local communities must be engaged as key stakeholders to ensure the technology alleviates regional water stress. A stepwise scaling approach is recommended to validate long-term performance and integrate this technology into sustainable water management in the mining industry.

It is essential to note that, from an operational perspective, bioreactors exhibit more fragile intrinsic stability compared to conventional technologies, such as reverse osmosis or ion exchange. The fundamental reason is their reliance on living microorganisms, which are sensitive to fluctuations in pH, temperature, or the presence of toxic compounds. Perhaps the most significant challenge lies in the scaling process: it is not merely about increasing the reactor size but about ensuring that biological conditions remain homogeneous throughout the larger system. While the process can indeed operate passively once stabilized, it requires that these critical parameters remain within very defined margins. In our experience, this very microbiological sensitivity is what enables sustainable treatment with low energy consumption and the potential for resource recovery. Therefore, bioreactors should not be viewed as a direct replacement for physicochemical technologies but rather as a strategic complementary alternative, whose value is most significant in applications where their environmental advantages justify the need for stricter environmental control.

Before interpreting our findings further, we must note a series of limitations inherent to its developmental stage. The primary constraint is the gate-to-gate analysis scope, necessitated by the ongoing scaling process of bioreactor technology. This restricts access to comprehensive industrial-scale operational data required for broader life cycle assessments; nevertheless, results obtained within these boundaries remain robust and validate the scaling strategy. A further limitation is the absence of an uncertainty analysis for the life cycle inventory data, which would enhance the reliability of the environmental impact profiles; future research should include such an assessment as the technology scales. Additionally, the socio-environmental analysis relied on a single bioreactor configuration, which limited the identification of potential improvements achievable through comparative studies of alternative designs. Furthermore, the assessment of community impacts lacked integration

with qualitative analyses (e.g., interviews), which would have enhanced contextual depth and reinforced the robustness of quantitative findings generated through tools like SimaPro.

Notwithstanding these limitations, this research provides a robust framework for socio-environmental assessment to validate industrial technologies, establishing key metrics that enable the transition toward industrial symbiosis models in extractive sectors. The research demonstrates that the bioreactor outperforms conventional alternatives across nearly all categories assessed within both the S-LCA and E-LCA. Crucially, we identified that its reduced social burden, particularly regarding community impacts, stems directly from its minimal resource requirements and simplified operational processes, a critical advantage in mining contexts with socio-environmental tensions, such as Chile. Environmentally, bioreactors exhibit the lowest normalized impacts in key categories, including global warming and human carcinogenic toxicity, due to their energy and material efficiency. The core contribution validates how this integrated performance embodies industrial ecology principles, holistically optimizing life cycle outcomes beyond mere technical efficiency while minimizing externalities. Furthermore, technology provides concrete solutions for water security in arid regions by transforming tailings water into reusable resources, thereby alleviating regional water stress and enhancing climate resilience. Notably, its alignment with Chilean sustainability policies and facilitation of mining's transition toward a circular economy, where waste minimization and industrial symbiosis enable scalable decoupling of economic growth from environmental impacts and social conflicts, establishes bioreactors as catalysts for industrial decarbonization and sustainable territorial development. This synergy of operational, strategic, and regulatory benefits positions technology as a transformative model for extractive industries.

The findings of this study align with previous research on sustainable metallurgical wastewater management [21,22], demonstrating that low-complexity bioremediation systems have lower sustainability impacts than traditional water softening methods. While previous studies emphasized technical efficiency of membrane processes [19,50,51], our integrated S-LCA/E-LCA approach substantiates recent theoretical frameworks positing that socio-environmental trade-offs are a critical factor to consider for real-world viability in water-scarce regions [52]. Notably, we extend Zannini et al. [53]'s observations about community acceptance barriers by quantitatively demonstrating how operational simplicity directly reduces social burdens, resolving a key knowledge gap in industrial metabolism literature. The observed policy alignment echoes Guzman et al. [54] call for context-specific sustainability solutions in Chilean mining, while our circular economy contribution dovetails with global paradigms advocating waste-as-resource transformations [6]. Collectively, these findings advance a paradigm shift in metallurgical water treatment where technical simplicity, socio-environmental coherence, and policy relevance converge to address both sustainability challenges and operational pragmatism in resource-constrained settings.

Our study highlights several key directions for future research and practice. The study must advance beyond current analytical boundaries by implementing comprehensive *cradle-to-grave* Life Cycle Assessment/Costing frameworks, overcoming existing gate-to-gate limitations to quantify full socio-environmental impacts and economic viability across mining value chains. Priority should be given to comparative configuration studies that optimize bioreactor designs for industrial symbiosis networks, integrating circularity metrics and community impact assessments through mixed methods approaches (quantitative indicators and stakeholder interviews).

5. Conclusions

This study presents a comprehensive gate-to-gate socio-environmental evaluation of a bioreactor-based technology for treating mining tailings water, comparing it to conventional

alternatives from an industrial metabolism perspective. The findings suggest that the bioreactor demonstrates strong potential for sustainability benefits, showing comparatively lower impacts in several key categories, including greenhouse gas emissions, due to its low energy demands, streamlined infrastructure, and avoidance of hazardous chemicals. Socially, under the assessed framework, bioreactor technology presented a favorable risk profile compared to the alternatives, aligning with principles of sustainable development for the mining sector. The analysis also identified critical supply chain hotspots, notably gravel and pine needles, which represent primary opportunities for targeted improvements. This case study illustrates how industrial ecology principles, such as resource valorization, can be applied to water management, potentially transforming tailings water into a secondary resource. While the gate-to-gate scope limits broader assertions, the results indicate that bioreactor technology is a promising candidate for advancing circular economy goals in the mining industry, particularly in water-scarce regions. Future work involving a complete life cycle assessment and uncertainty analysis is necessary to confirm these preliminary findings at full scale. Ultimately, this research highlights a practical approach for reducing the environmental footprint of mining operations and transitioning toward more regenerative models.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17209269/s1, Table S1: Inputs and Outputs for the anion exchange-based water softening process, per 1 kg of softened water ; Table S2: Inputs/Outputs for water softening technology using nanofiltration, per 1 kg of softened water; Table S3: Inputs/Outputs for softwater production using reverse osmosis treatment, per 1 kg of softwater; Table S4: Inputs/Outputs to produce 1 ultrafiltration module; Table S5: Inputs/Outputs to produce One 8-Inch Spiral-Wound Seawater reverse osmosis module.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
E-LCA	Environmental Life Cycle Assessment
SDHB	Social Hotspot Database
pbf	Plant-based fiber
ocr	Other crops

gro	Other grains
ctl	Cattle
i_s	Iron & Steel
nmm	Non-metallic Minerals

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