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Environmental Sustainability Assessment of pH-Shift Technology for Recovering Proteins from Diverse Fish Solid Side Streams

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Abstract: The demand for clean-cut seafood fillets has led to an increase in fish processing side streams, which are often considered to be low-value waste despite their potential as a source of high-quality proteins. Valorizing these side streams through innovative methods could significantly enhance global food security, reduce environmental impacts, and support circular economy principles. This study evaluates the environmental sustainability of protein recovery from herring, salmon, and cod side streams using pH-shift technology, a method that uses acid or alkaline solubilization followed by isoelectric precipitation to determine its viability as a sustainable alternative to conventional enzymatic hydrolysis. Through a Life Cycle Assessment (LCA), five key environmental impact categories were analyzed: carbon footprint, acidification, freshwater eutrophication, water use, and cumulative energy demand, based on a functional unit of 1 kg of the protein ingredient (80% moisture). The results indicate that sodium hydroxide (NaOH) use is the dominant environmental impact driver across the categories, while energy sourcing also significantly affects outcomes. Compared to conventional fish protein hydrolysate (FPH) production, pH-shift technology achieves substantial reductions in carbon footprint, acidification, and water use, exceeding 95%, highlighting its potential for lower environmental impacts. The sensitivity analyses revealed that renewable energy integration could further enhance sustainability. Conducted at a pilot scale, this study provides crucial insights into optimizing fish side stream processing through pH-shift technology, marking a step toward more sustainable seafood production and reinforcing the value of renewable energy and chemical efficiency in reducing environmental impacts. Future work should address scaling up, valorizing residual fractions, and expanding comparisons with alternative technologies to enhance sustainability and circularity.

Keywords: environmental sustainability; life cycle assessment; carbon footprint; freshwater eutrophication; acidification; water use; fish side streams; pH-shift; seafood side streams valorization

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1. Introduction

Global fisheries and aquaculture production reached 214 million tons in 2020, and it is assumed that the sector will play an important role in contributing to global food security in the future [1]. A significant driver of this increasing demand lies in the sector's capacity to supply high-quality animal-based proteins to an ever-expanding global population.

Concurrently, these industries generate substantial side streams, such as heads, skins, tails, and back-bones. Depending on the methods employed, these can account for up to 70% of total production [2]. Often perceived as low-economic value side streams, or sometimes even as waste, reintegrating these materials into the supply chain can manifest both environmental and economic benefits [3].

When fisheries and aquaculture side streams are treated as waste, such as in rural areas lacking efficient transport, they may cause significant environmental problems by posing a risk of pollution and damaging the ecosystem [4]. Where logistics and infrastructures are in place, most fishery and aquaculture side streams are currently utilized for low-value products such as fish oil, fishmeal, fertilizer, and pet food. However, as recent studies have revealed valuable nutritional compounds in these underutilized resources, such as fish muscle proteins, fish oil, and fish bones [5,6], there are incentives for increased uses, including directly as food. The latter would turn these nutrients into resources for humans providing the potential for these resources to contribute to global food security. Some side streams, for example, fish frames, contain significant amounts of muscle proteins that are nutritious and digestible [7,8]. In order to valorize these protein-rich resources, the combination of advanced processing technologies has gained interest in recent years, especially for applications in foods, feeds, and nutraceuticals, taking advantage of the current consumer trend towards more environmentally sustainable products derived from these materials [9].

Although side streams from fisheries contain a significant amount of protein, there are various difficulties in utilizing them [10]. For instance, different side streams may contain specific compositions or may be contaminated by other tissues, which increases the complexity of processing these types of materials [11]. In this regard, various mechanical and chemical techniques are utilized to obtain nutritional components from fish side streams; nevertheless, these techniques consume a significant amount of energy and may harm the target molecules [12].

The pH-shift technology emerges as a promising solution for handling complex and even unsorted seafood side streams. This gentle, water-based method allows for the simultaneous recovery of aquatic proteins and oils from seafood side streams [13]. Based on acid or alkaline solubilization of muscle proteins followed by isoelectric precipitation of cold-soluble proteins, the pH-shift process provides functional protein ingredients with independent product formation capabilities [14]. Compared to conventional methods, it offers advantages such as higher protein yields, greater lipid reductions, and enhanced gel-forming properties of proteins [15]. In contrast to enzymatic hydrolysis, the pH-shift technology separates proteins from other side stream components (e.g., bones and fats) without inducing protein degradation. Additionally, the quality of the seafood proteins and lipids is better preserved since the entire pH-shift process is conducted at cold temperatures. Furthermore, proteins recovered using the pH-shift process can be used in their wet form (e.g., as mince) for product development, which avoids the energy-intensive drying step required at the end of the enzymatic hydrolysis process, thereby expanding the product's application potential.

Despite the promising potential of pH-shift technology for the utilization of fish side streams, it is crucial to investigate the environmental implications of this process. The food industry, particularly terrestrial animal protein production, is responsible for significant environmental consequences such as climate change, water use, biodiversity loss, and habitat destruction, which have recently attracted considerable attention [16,17]. To reduce and mitigate these consequences, it is essential to analyze the relevant production processes that are applicable to aquatic food protein sources.

In this context, a Life Cycle Assessment (LCA) is a capable analytical tool for qualitatively measuring environmental burdens. An LCA helps identify environmental hotspots and provides valuable information to decision-makers [18]. Therefore, analyzing the environmental performance of emerging techniques like the pH-shift process from an LCA perspective is crucial. A greater understanding of the environmental impacts of side stream valorization is valuable for both research and society at large [19]; in this sense, LCAs are an important tool [20].

Previous studies have utilized LCAs to assess similar processes. For instance, a recent study performing an LCA for a protein ingredient derived from cross-processing herring heads and backbones with lingonberry pomace revealed that a model product produced from this protein ingredient performed well compared to a reference food product [21]. In another study, Coelho et al. (2022) [22] investigated the environmental impacts of cross-processing herring side streams using different antioxidant-rich materials ("helpers") through an LCA and found that no side stream–helper combination had less impact in different impact categories. However, despite these studies, the actual environmental impact of the pH-shift process applied to different types of side streams from various fish species and its comparison with other techniques remains unexplored.

Given the importance of assessing the potential environmental impacts of innovative technologies to valorize side streams from fish industries, the present study aims to evaluate the environmental sustainability of protein ingredient extraction using pH-shift technology from solid fish filleting side streams through an LCA. The objectives are to identify the environmental hotspots and determine the most suitable type of side stream for processing with the pH-shift technology. Side streams from cod, salmon, and herring have been targeted in this study, which represent the most abundant side streams in Scandinavia with the highest potential for valorization.

Beyond hotspot identification, this research presents a comparative analysis with enzymatic hydrolysis, a conventional method for processing solid fish side streams. By presenting quantitative data sourced from a pilot-scale plant through an LCA, this study fills the identified knowledge gap. The results provide valuable insights for decision-makers regarding the environmental impact of the emerging pH-shift technology.

2. Materials and Methods

As explained earlier, the LCA methodology was applied to evaluate the potential environmental impacts of valorizing different fish side streams and to provide valuable insights for decision-making and resource allocation in the fish industry. Solid side streams from different fish species were processed with the pH-shift technology to extract protein ingredients. The side streams that were addressed were selected based on their protein content and were extracted in pH-shift trials in a pilot plant in Sweden, as part of the EU project WaSeaBi. WaSeaBi aims to bring a sustainable approach to the use of aquatic resources by developing efficient and sustainable storage solutions, classification technologies, and decision tools for side streams from the aquaculture and fish industries.

2.1. System Description

Multiple samples of herring (*Clupea harengus*), salmon (*Salmo salar*), and cod (*Gadus morhua*) frames and heads were collected from local fish producers including Sweden Pelagic AB and FiskIdag AB and transported under cold condition to the pilot plant in Ellös, Sweden. The pilot has a capacity of 1 m^3/h and uses small-scale industrial units. There, protein extractions were conducted using pH-shift processing technology, and analytics such as protein yield and protein level of the final ingredient were followed. Herring heads were not taken into consideration due to their low protein yield and high blood content. A primary screening of these side streams was conducted at laboratory scale, followed by pH-shift processing at pilot scale.

The processing of herring, cod, and salmon side streams (head and frame) using the pH-shift technology was carried out according to the procedures outlined by Abdollahi & Undeland (2018) [23] on laboratory-scale protein isolate produced from salmon, cod, and herring side streams. Fresh fish side streams were first subjected to grinding using a meat mincer (Sydelmann AE 130, Berlin, Germany) and then mixed with water. During the pH-shift process, the extraction involved utilizing high pH levels (>10) to solubilize the muscle proteins in water using food-grade NaOH (Sigma, Darmstadt, Germany), followed by centrifugation to separate the solubilized proteins from undissolved materials with different densities. The solubilized proteins were recovered through isoelectric precipitation, typically at a pH of 5.5, by acidification using HCl (Sigma, Germany), and further dewatered using the centrifugation method. The process was conducted at pilot scale with the following volumes of fish: water homogenates between 0.5 and 1 m^3 handled 100–200 kg of fish per batch.

2.2. Life Cycle Assessment

Within the scope of this study, the environmental impacts associated with the production of protein ingredients from herring, salmon, and cod side streams using pH-shift technology were assessed through LCA. According to the ISO 14040:2006 [24] and ISO 14044:2006 standards, the LCA framework includes the following phases: (i) goal and scope definition; (ii) life cycle inventory; (iii) life cycle impact assessment; and (iv) interpretation [18]. Thus, this section is shaped according to the LCA framework.

2.2.1. Goal and Scope Definition

As mentioned previously, the main objective of this study was to assess the potential environmental impacts of processing different fish side streams using pH-shift technology from a life cycle perspective. Thus, this study aimed to assess the environmental sustainability of the protein extraction process from solid fish side streams. The selected functional unit was the production of 1 kg of the protein ingredient (80% moisture) either from herring frames, salmon frames and heads, or cod frames and heads.

The analysis followed a cradle-to-gate approach, focusing on the production of the protein ingredient. System boundaries included grinding and mixing, solubilization, separation, pH readjustment (i.e., isoelectric precipitation), dewatering, mixing, forming, and freezing. Figure 1 illustrates the system boundaries established for this assessment. The figure aligns with the stages outlined by Abdollahi and Undeland (2019) [25]. As shown in the process flow diagram, after the grinding and mixing step, the mince dispersed in water underwent pH adjustment using NaOH. It was then subjected to centrifugation, where the mid-layer containing soluble proteins was separated from the floating lipid layer using centrifugation, while insoluble residues containing fat layer and bones were retained. After adjusting the pH of the separated protein layer with HCl, a second centrifugation step was used for dewatering. The fat layer and bones, which were not processed in the pilot plant, were considered burden-free by-products and thus were excluded from the system boundaries, aligning with the paradigm shift in life cycle assessment applied to waste materials [26].

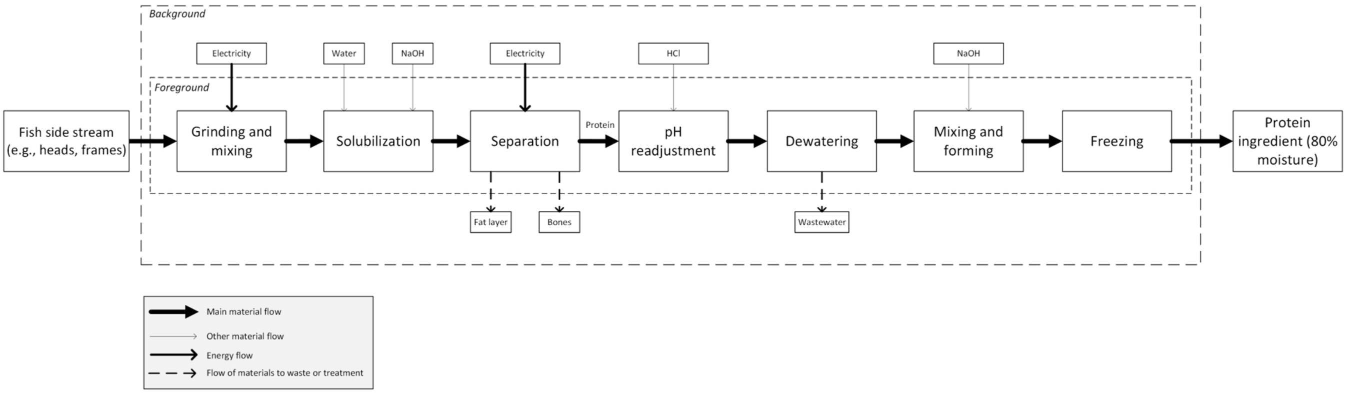

Figure 1. Definition of system boundaries for pH-shift technology for different fish solid side streams.

2.2.2. Life Cycle Inventory

The data sourced for the LCA study was collected from a pilot plant placed in Ellös, Sweden, supplemented by the ecoinvent v3.10 database for background data. Datasets representing the European market (RER, market for) were utilized for all processes, with two exceptions: sodium hydroxide (NaOH), for which only global (GLO) data were available, and electricity, for which the Swedish electricity mix at medium voltage was applied.

Table 1 presents the inventory used in the analysis. Pilot scale trials processed 1 ton of each of the side streams.

Table 1. Life cycle inventory to produce 1 kg of protein ingredient (80% moisture) from five different side stream fractions via pH-shift technology [i].

		Herring	Salmon		Cod	
		Frames	**Frames**	**Heads**	**Frames**	**Heads**
Inputs	Unit					
Side streams	kg	2.00	2.00	3.23	2.56	2.78
Water	m^3	0.006	0.006	0.010	0.008	0.008
NaOH [ii]	kg	0.038	0.022	0.037	0.027	0.031
HCl [ii]	kg	0.033	0.020	0.033	0.024	0.028
Electricity *	kWh	0.306	0.306	0.306	0.306	0.306
Outputs						
Protein	kg	1.00	1.00	1.00	1.00	1.00
Wastewater	m^3	0.005	0.006	0.010	0.008	0.008
Fat layer	kg	0.100	0.170	1.129	-	-
Bones	kg	0.300	0.320	1.226	0.974	1.083

[i] Each side stream fraction is represented in wet weight; some of them have experienced an increase in mass due to the increase in their moisture content during the process. [ii] Chemicals are at a concentration of 4N during the process. * Sweden electricity mix.

As described in the goal and scope definition section, the analysis did not comprise the fat layer and bones. Nevertheless, it is worth noting that they can be repurposed to produce fish oil and collagen, respectively. However, processing these side streams may also increase environmental burdens due to the energy and resources required for their valorization.

2.2.3. Life Cycle Impact Assessment

To comprehensively assess the environmental impacts of the cases under study, SimaPro® (version 9.6) software was employed, utilizing the Environmental Footprint 3.0 (EF 3.0) impact assessment method. EF 3.0 was selected because it is the latest and most robust method recommended by the European Commission for environmental impact assessments [27,28]. The assessment focused on several relevant impact categories, including climate change, acidification, freshwater eutrophication, and water use. These impact categories are particularly pertinent due to emissions associated with electricity generation, potential release of acidic substances from chemical use, nutrient loads in wastewater discharges, and significant water consumption in the processes [29,30]; similarly, those indicators were chosen based on their significant environmental relevance to fisheries operations, as identified in previous studies [16,31]. Additionally, the cumulative energy demand (CED) indicator was chosen to evaluate total energy consumption throughout the processes, providing insights into energy efficiency and opportunities to reduce environmental impacts associated with electricity use [32]. These categories and indicators were selected based on their relevance to the environmental burdens associated with chemical and energy-intensive processes, aligning with best practices in life cycle assessments for such systems as documented in key methodological guides and studies [33,34].

2.2.4. Interpretation

A contribution analysis was performed for all assessments to identify the main contributors to the selected impact categories. Subsequently, an uncertainty analysis using Monte Carlo simulations in SimaPro® software was conducted to evaluate the standard deviation of the obtained LCA results for all assessed indicators. It is important to note that this uncertainty analysis was applied only to the background system, specifically the selected processes from ecoinvent. Finally, a sensitivity analysis was conducted on the electricity source to determine its influence on the LCA results; the European average electricity mix at medium voltage was considered as an alternative to the Swedish electricity mix (medium voltage).

3. Results and Discussion

This section presents the results based on the impact categories selected in the life cycle impact assessment phase.

Figure 2 illustrates the results for the climate change impact category. The pH-shift processing of herring frames shows the highest carbon footprint, with approximately 0.412 kg CO_2 eq./kg of protein, among the side streams examined. In contrast, salmon frames demonstrate the lowest impact, with a carbon footprint of about 0.132 kg CO_2 eq./kg of protein. The predominant factor influencing the carbon footprint across all side streams analyzed is the use of sodium hydroxide, which accounts for approximately 88% to 96% of the total environmental impact. Specifically, in the case of herring frames, NaOH contributes about 96% of the carbon footprint.

The elevated contribution of NaOH in processing herring frames is likely attributed to the higher consumption required during the alkaline solubilization step. Herring frames possess a higher muscle-to-bone ratio compared to cod and salmon, which enhances their buffering capacity under alkaline pH conditions. This necessitates increased amounts of NaOH to achieve the desired pH levels during protein isolation [25]. The production of NaOH is particularly energy-intensive due to the substantial electricity requirements of its manufacturing processes, which significantly influences its carbon footprint [35,36].

Following NaOH, electricity consumption was identified as the second-largest contributor to the carbon footprint across all side stream types, although its impact is substantially lower, contributing approximately 2–3% of the total carbon footprint. Hydrochloric acid (HCl) usage, water consumption, and wastewater generation have comparatively minor impacts, each accounting for less than 1% of the total environmental impact.

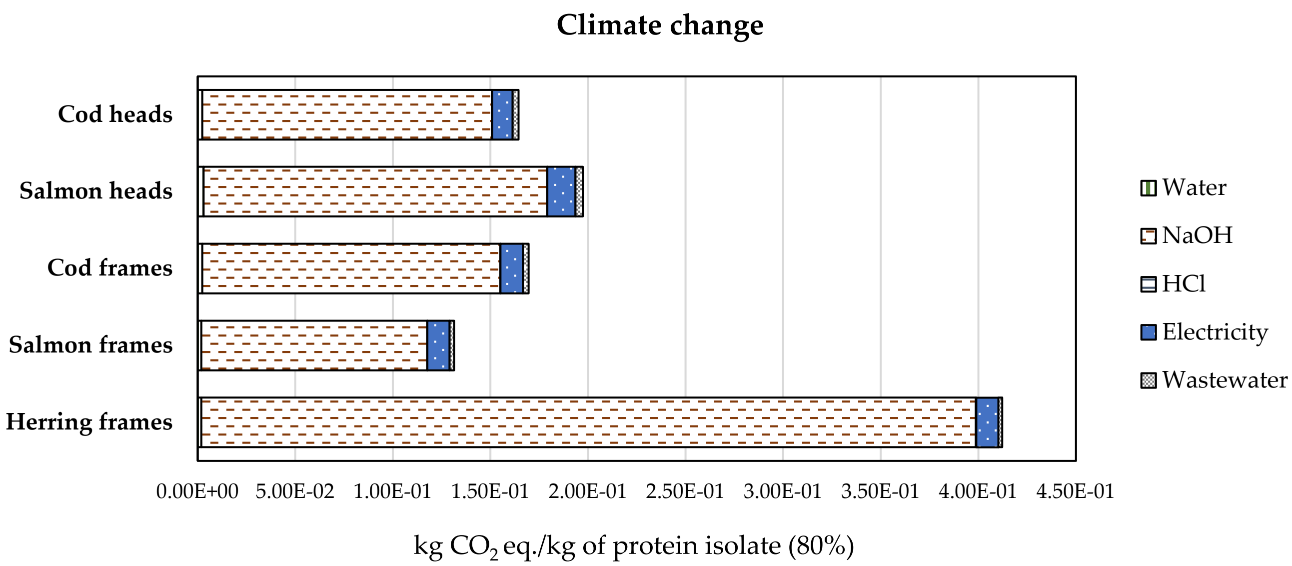

Figure 2. Climate change impact category results for protein extraction from solid fish side streams using pH-shift technology.

These findings underscore the critical role of chemical usage, particularly NaOH, in the environmental performance of the pH-shift protein isolation process. Reducing NaOH consumption through process optimization or by substituting it with less impactful alternatives could potentially mitigate the carbon footprint associated with this processing method. Additionally, sourcing NaOH produced using more energy-efficient technologies or renewable energy sources may further reduce environmental impacts, as the electricity used in NaOH production is a significant contributor to its carbon footprint [37]. The lower carbon footprint observed for salmon frames is due to a reduced NaOH requirement, resulting from differences in the chemical composition and buffering capacity of the raw material. This highlights the importance of considering the specific characteristics of each side stream in both process design and environmental impact assessments.

Figure 3 presents the acidification impact category results, where herring frames presented with the highest impact. Similar to the findings in the carbon footprint indicator, the utilization of NaOH remains the primary driving force behind the acidification impact for all side stream types. NaOH accounts for approximately 89% to 96% of the total acidification impact, paralleling its significant contribution to the carbon footprint. Specifically, for herring frames, NaOH contributes about 96% of the acidification potential. The significant impact of NaOH on acidification is primarily due to the emissions associated with its production process. The industrial production of NaOH typically involves the chlor-alkali process, which is energy-intensive and often relies on electricity generated from fossil fuels. The combustion of these fuels in power plants leads to the emission of acidifying substances such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) [37].

On the other hand, utilities demonstrate a comparatively minimal environmental impact. Consequently, reducing the consumption of these chemicals, especially NaOH, could markedly decrease the environmental impacts associated with both carbon footprint and acidification. This suggests a potential strategic direction for mitigating environmental impacts in fish processing operations.

Based on the findings of the freshwater eutrophication impact category, as depicted in Figure 4, the pH-shift processing of herring frames presents again with the highest impact among the examined side streams, with approximately 3.02×10^{-5} kg P eq/kg of protein, while salmon frames showed the lowest impact, with a eutrophication potential of about 1.63×10^{-5} kg P eq/kg of protein. The primary factors influencing the freshwater eutrophication impact across all analyzed side streams are the use of sodium hydroxide (NaOH) and wastewater generation. For herring frames, NaOH consumption is the dominant contributor, accounting for approximately 72% of the total eutrophication potential. This significant contribution is linked to the phosphorus emissions associated with NaOH production, which can lead to nutrient enrichment in freshwater bodies and subsequent eutrophication.

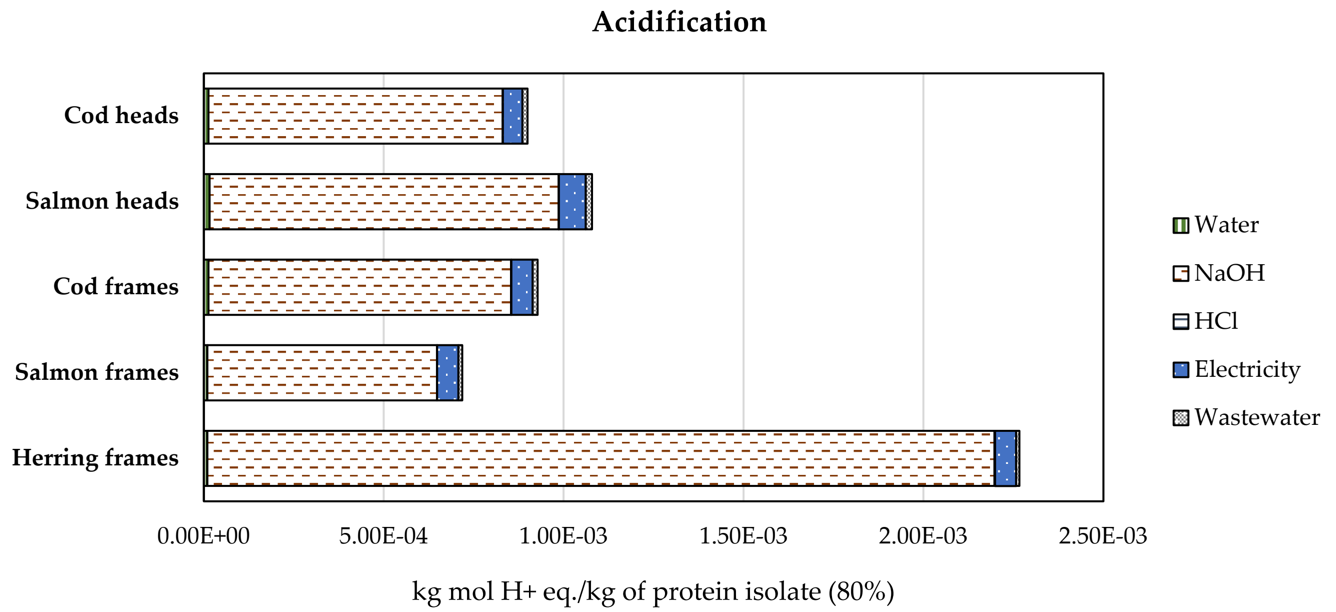

Figure 3. Acidification impact category results for protein extraction from solid fish side streams using pH-shift technology.

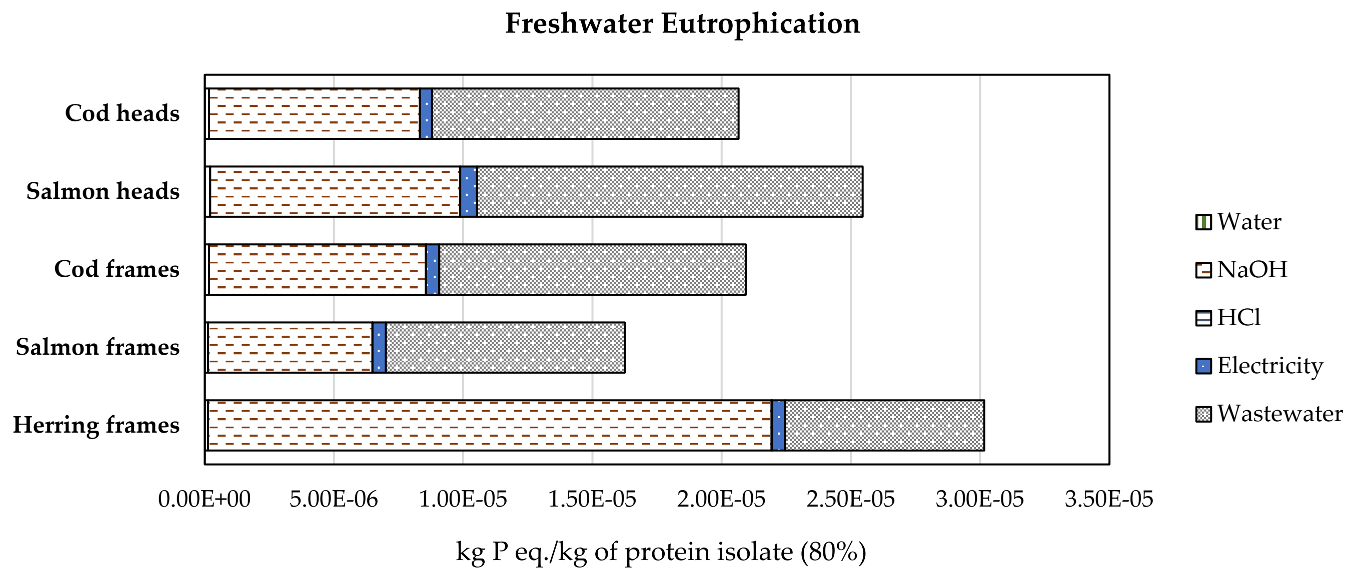

Figure 4. Freshwater eutrophication impact category results for protein extraction from solid fish side streams using pH-shift technology.

In contrast, for salmon heads, wastewater generation emerges as the most significant contributor, responsible for approximately 59% of the total impact due to the substantial amount of nutrient-rich wastewater produced during processing. The effluent contains organic matter and nutrients, including phosphorus, which can contribute to freshwater eutrophication if not properly treated before discharge. Efforts to reduce wastewater, or to reuse it internally within the plant, would be beneficial in decreasing these negative consequences.

As expected, the results in the water use impact category, presented in Figure 5, illustrate that the primary contributors are the direct water consumption in the process and the use of NaOH. For herring frames, direct water consumption accounts for approximately 65% of the gross water use impact, contributing 0.253 m^3 depriv./kg of protein. NaOH usage is also a significant contributor, adding 0.364 m^3 depriv./kg of protein, which constitutes about 93% of the impact of gross water use before considering wastewater. Furthermore, it is worth noting that wastewater shows a negative impact within this category, leading to a reduction in the overall environmental impact. Since the water use impact category is based on water depletion according to scarcity, wastewater generation is defined here as a mitigating factor [38]. By addressing water consumption while implementing sustainable wastewater management practices, significant progress can be made towards minimizing the environmental burdens in the water use impact indicator.

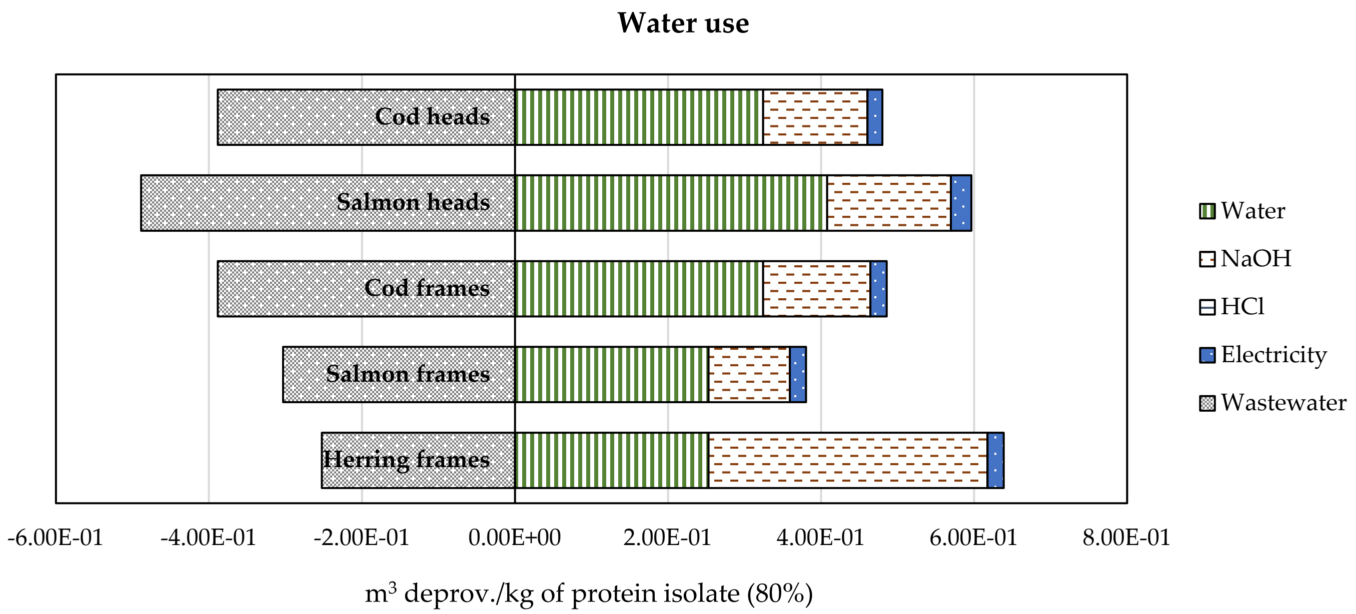

Figure 5. Water use impact category results for protein extraction from solid fish side streams using pH-shift technology.

The pH-shift processing of herring frames shows the highest cumulative energy demand among the assessed side streams, with a total CED of approximately 8.43 MJ/kg of protein, while salmon frames demonstrate the lowest impact, with a total CED of about 4.29 MJ/kg of protein (Figure 6). The primary contributors to the CED across all side streams are the use of NaOH and electricity consumption. For herring frames, NaOH usage is the dominant contributor, accounting for approximately 69% of the total energy demand (5.84 MJ/kg of protein), followed by electricity consumption, which contributes about 30% (2.52 MJ/kg of protein). Similar trends are observed in the other side streams, where NaOH and electricity collectively account for the majority of the energy demand, although their relative contributions vary depending on the specific side stream processed.

These findings align with the trends observed in previous impact categories such as climate change, acidification, and freshwater eutrophication, where NaOH consumption consistently emerged as a major environmental burden due to its energy-intensive production process.

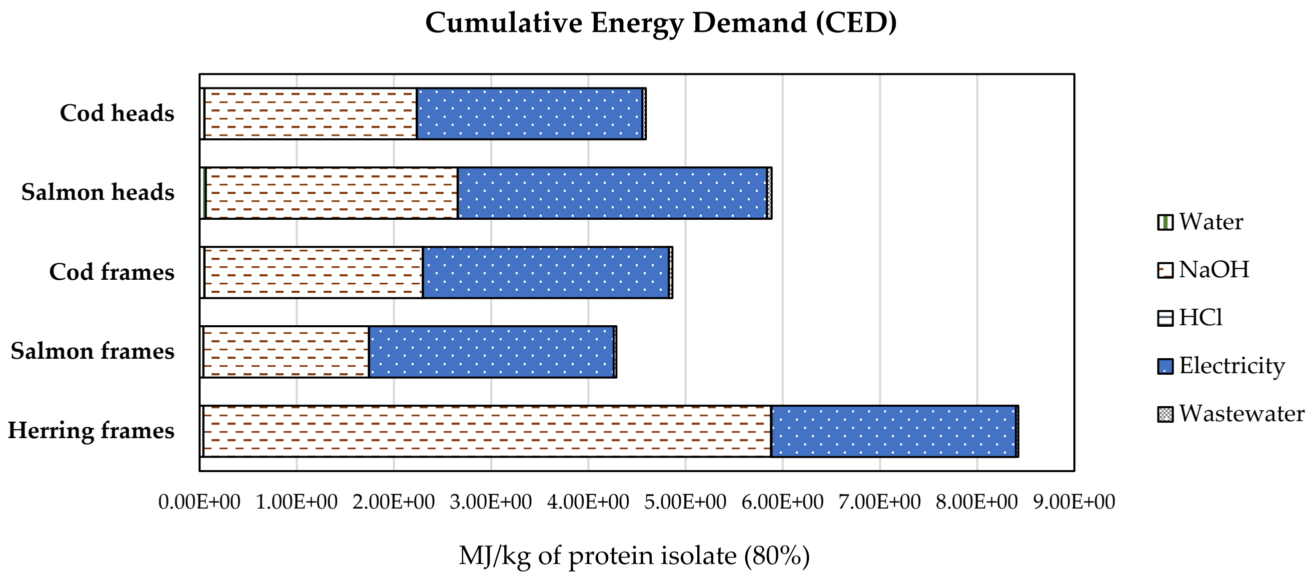

Figure 6. Cumulative energy demand impact category results for protein extraction from solid fish side streams using pH-shift technology.

The consistent prominence of NaOH and electricity consumption across multiple impact categories underscores their overarching influence on the environmental performance of the pH-shift protein isolation process. Reducing NaOH usage through process optimization, such as adjusting pH levels more efficiently, improving process control, or exploring alternative chemicals with lower energy footprints, could significantly mitigate the cumulative energy demand and associated environmental impacts. Similarly, enhancing energy efficiency in processing operations or sourcing electricity from renewable energy sources could further reduce the CED and contribute to lower impacts in the climate change category.

3.1. Uncertainty Analysis

An uncertainty analysis was conducted using Monte Carlo simulations to assess the robustness of the LCA results for all impact categories that were evaluated. As mentioned before, this analysis focused on the background system, specifically the processes selected from the ecoinvent database, as variability data for the foreground system (the pilot plant operations) was limited, and thus, it was treated deterministically.

For the different side streams assessed, the results indicated moderate to low uncertainty in the climate change and acidification impact categories. For instance, for herring frames, the mean global warming potential was calculated to be 0.389 kg CO_2 eq./kg of protein, with a coefficient of variation (CV) of 12.5%. Similarly, the acidification potential had a mean value of 0.00221 mol H^+ eq./kg of protein, with a CV of 12.8%. These relatively low CVs suggest that the estimates for these impact categories are robust and that the variability in background processes such as the production of sodium hydroxide (NaOH) and electricity does not significantly affect the overall results.

In contrast, higher uncertainty was observed in the freshwater eutrophication and water use impact categories. For herring frames, the freshwater eutrophication potential had a mean of 1.97×10^{-4} kg P eq./kg of protein and a CV of 49.5%, indicating substantial variability. This high uncertainty is primarily due to the variations in phosphorus emissions associated with background processes such as chemical production. The water use category exhibited even greater uncertainty, with a mean net water use of 0.687 m^3 depriv./kg of protein and a CV exceeding 2400%. Such extreme variability arises from the treatment of wastewater generation as a negative impact (credit) in water scarcity assessments and the sensitivity to regional water scarcity factors in the background data.

For salmon frames, similar patterns were observed. The climate change impact had a mean of 0.103 kg CO_2 eq./kg of protein and a CV of 13.7%, while the acidification potential was 0.000654 mol H^+ eq./kg of protein with a CV of 12.6%. These figures indicate moderate confidence in the results for these categories. However, the freshwater eutrophication potential showed a high CV of 41.1%, and the water use category again displayed significant uncertainty, with a CV of over 2350%.

The cumulative energy demand (CED) showed moderate uncertainty. For instance, herring frames had a mean CED of 1.493 MJ/kg of protein with a CV of 18.6%, while salmon frames had a mean of 0.824 MJ/kg of protein and a CV of 17.7%. These values suggest that, while there is some variability in the energy demand estimates due to background processes, the overall uncertainty is acceptable.

The higher uncertainty in the freshwater eutrophication and water use categories underscores the need for improved data quality and more precise modeling of background processes related to nutrient emissions and water consumption.

By acknowledging these uncertainties, stakeholders can focus on areas where data refinement is needed. For instance, collecting more detailed and region-specific data on phosphorus emissions and water use in chemical production can reduce variability. Additionally, incorporating variability data from the foreground system in future studies, especially as the technology scales up, will enhance the robustness of the LCA results.

3.2. Sensitivity Analysis

In this study, the LCA was modelled based on data from the pilot plant operating with the Swedish electricity mix (medium voltage), which relies on 43% renewable energy sources (EC Directorate-General for Energy, 2022). This resulted in a relatively low impact of electricity consumption in the climate change, acidification, freshwater eutrophication, and CED impact categories. In this context, a sensitivity analysis for electricity consumption was conducted using the European average electricity mix at medium voltage.

When the European average electricity mix was applied in the sensitivity analysis, there was a significant increase in the environmental impacts across all categories. In the climate change indicator, the carbon footprint for salmon frames increased by approximately 76%, rising from 0.131 kg CO_2 eq./kg of protein to 0.231 kg CO_2 eq./kg of protein. For herring frames, the carbon footprint increased by about 24%.

The contribution of electricity to the total carbon footprint increased markedly. For salmon frames, the share of electricity consumption in the carbon footprint rose from approximately 8.7% with the Swedish mix to 48.0% with the European average mix. Similarly, for herring frames, the electricity contribution increased from about 2.8% to 21.7%. This shift underscores the significant impact that the source of electricity can have on the overall environmental performance of the process.

Similar trends were observed in the acidification and freshwater eutrophication impact categories, with increases ranging from 23% for herring frames to 73% for salmon frames when using the European electricity mix. The higher emissions of acidifying substances and nutrients associated with fossil fuel-based electricity generation in the European mix contribute to these increases.

The CED also increased due to the higher primary energy requirements associated with electricity generation in the European mix, which relies more heavily on fossil fuels. For salmon frames, the CED increased from 4.29 MJ/kg of protein to 4.83 MJ/kg of protein, representing an increase of approximately 12.7%. For herring frames, the CED increased approximately 6.5%. This growth in the CED is primarily attributed to the higher energy inputs required for electricity production in the European mix compared to the Swedish mix.

These findings underscore the significance of the energy source used in processing side streams. In countries relying heavily on fossil fuel-based electricity generation, such as those represented in the European average mix, investing in green energy and increasing the share of renewable energy sources in the electricity grid can play a crucial role in mitigating environmental impacts across multiple categories, including climate change, acidification, and CED.

The consistent trends across these impact categories highlight the overarching influence of electricity sourcing on the environmental performance of the pH-shift protein isolation process. The substantial increases in impacts when using the European electricity mix demonstrate that electricity consumption can become a more dominant contributor, especially in categories like climate change and CED, where its relative share of the total impact increases significantly. For example, in the climate change category for salmon frames, electricity's contribution rises from 8.7% to 48.0%, making it the dominant factor when using the European mix.

Therefore, to enhance the sustainability of fish processing operations, it is imperative to consider not only process optimization and resource efficiency, but also the sourcing of cleaner energy.

3.3. Limitation of the Analysis and Future Perspectives

The main limitation of this study was the determination of system boundaries as cradle-to-gate due to the data limitations. However, it is important to note that more comprehensive and accurate results can be achieved through an enhanced system boundary, which would allow for a broader assessment.

Moreover, the inclusion of residual fractions formed during pH-shift processing, specifically the fat layer and bones, in the system boundaries holds significant importance for the outcomes. In this study, these residuals were not valorized; however, they present an opportunity for further processing into valuable products such as fish meal, oil, or collagen. The production of fish meal and oil from these residues would require additional resources and energy inputs, potentially increasing the environmental burdens associated with their processing. However, these products could substitute alternative protein and fat sources, such as soymeal and rapeseed oil, which are commonly used in animal feed and other applications. By displacing the need for these alternative products, the valorization of residual fractions could offset some of the environmental impacts, potentially resulting in net environmental benefits. Including the valorization of the fat layer and bones in the system boundaries would allow for a more holistic assessment of the environmental impacts and benefits of the pH-shift protein isolation process. This approach aligns with the principles of a circular economy and resource efficiency, promoting the utilization of all fractions of the raw material to minimize waste and maximize value creation [39].

Another limitation is that the current analysis is based on pilot-scale data, reflecting the medium Technology Readiness Level (TRL) of the pH-shift processing technology. As the process scales up to industrial levels, improvements in efficiency, equipment utilization, and process optimization are expected, which could lead to reductions in environmental impacts. Future studies should consider these potential improvements and update the life cycle inventory accordingly to provide a more accurate representation of the industrial-scale environmental performance.

In terms of comparative analyses, while this study did not directly compare the pH-shift protein isolation process with other protein recovery technologies, such as enzymatic hydrolysis, it is noteworthy that the current carbon footprint of the pH-shift process for the different side streams analyzed is lower compared to the carbon footprint reported for fish protein hydrolysate (FPH) production. For instance, the carbon footprint of FPH production has been reported as approximately 1.88 kg CO_2 eq./kg of processed fish protein hydrolyzed (dry weight) [40]. In contrast, the carbon footprint for the pH-shift process ranges from 0.131 to 0.412 kg CO_2 eq./kg of protein, indicating a potentially lower environmental impact. Moreover, a recent study by Bashiri et al. [41], assessed the environmental and economic life cycle of enzymatic hydrolysis-based extraction of fish protein and oil from Atlantic mackerel processing residues. They found that the climate change impact of the whole process was 0.073 kg CO_2 eq. per 1 g of FPH. This value is significantly greater than the carbon footprints reported in this study and previous literature.

FPH production typically involves the use of proteolytic enzymes to hydrolyze fish proteins, followed by energy-intensive processes such as heating and drying to produce a stable powder form [42]. The higher energy consumption associated with these steps contributes to the greater carbon footprint of FPH. Moreover, FPH production may also involve longer processing times and additional inputs, further increasing the environmental impacts [40].

Nevertheless, it is important to emphasize that direct comparisons should be made cautiously, considering differences in system boundaries, functional units, and data sources. Future work should aim to conduct a comprehensive comparative life cycle assessment between the pH-shift process and alternative protein recovery methods, using consistent methodologies and updated data reflecting industrial-scale operations. For instance, the recovered protein is a versatile mince-like product with a mild fish flavor that can be either directly cooked and consumed as a seafood product or be used as an intermediate product for the development of a wide variety of restructured seafood products such as fish burgers, fish cakes, fish sausages, nuggets, or even as a mince replacement in lasagna, dumplings, etc.

4. Conclusions

This study conducted a comprehensive LCA on the use of pH-shift processing technology for extracting protein ingredients from herring, cod, and salmon side streams, with the aim of evaluating its environmental hotspots.

When considering all environmental impact categories, it is evident that the salmon frame value chain presented with the lowest environmental impacts among all the side streams. This low impact is attributed to the higher protein yield, thus limiting the usage of chemicals with high environmental implications, such as NaOH and HCl.

Throughout the analysis of the various side stream types, it became clear that NaOH consistently contributes the most substantial environmental impact across all categories. This result is due to the environmental burden arising from emissions during its production processes. On a positive note, utilities, such as water and electricity, have a relatively lower impact compared to chemicals. This finding suggests that focusing on optimizing chemical usage can lead to considerable improvements in reducing the overall environmental footprint. In addition, the re-utilization of side-fractions emerging in the pH-shift process can further reduce the environmental impacts.

Though this study took into account the Swedish electricity mix, with 43% renewables, a sensitivity study was done to identify the potential impact if the average European electricity mix is considered. This analysis showed that the carbon footprint increased by approximately 24% for herring frames and by 76% for salmon frames when the European mix was considered. Similar increases were observed in other environmental impact categories; for instance, acidification and freshwater eutrophication impacts increased by 23% to 73%, depending on the side stream analyzed. These findings emphasize the importance of integrating renewable energy sources in secondary processing operations to mitigate environmental impacts effectively.

Despite the limitations of this study, the findings provided valuable insights for decision-makers and stakeholders in the fishing and aquaculture industries. In future studies, a cradle-to-grave LCA, with the inclusion of side-fraction valorization, would produce more comprehensive results.

As the global demand for fishery products increases, the importance of maximizing resource utilization and minimizing environmental impacts becomes ever more critical to sustainability. The innovative utilization of fish side streams through pH-shift technology offers an avenue to achieve these goals. By valorizing fish side streams into high quality proteins with the possibility to also recover nutritional compounds from side-fractions (e.g., omega-3 fatty acids, collagen), pH-shift technology can contribute to sustainable resource management.

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