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A comparative life cycle assessment of cross-processing herring side streams with fruit pomace or seaweed into a stable food protein ingredient

Carla R.V. Coelho[a], Gregory Peters[a,*], Jingnan Zhang[b], Bovie Hong[b], Mehdi Abdollahi[b], Ingrid Undeland[b]

[a] Division of Environmental Systems Analysis (ESA), Department of Technology Management and Economics, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden
[b] Division of Food and Nutrition Science (FNS), Department of Biology and Biological Engineering, Chalmers University of Technology, SE-412 96, Gothenburg, Sweden

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ABSTRACT

One approach to improve the sustainability of food processing is the recovery of valuable compounds from food industry's side streams. In this study a life cycle assessment (LCA) was used to quantify the potential environmental impacts of cross-processing herring side streams with different antioxidant-rich biomasses, so-called helpers, for the extraction of a protein ingredient that is stable against lipid oxidation. New primary experimental data was combined with literature values to model cross-processing of herring with different helpers, namely, lingonberry pomace, apple pomace, and brown and green seaweed. Different addition ratios and delayed addition of the pomace were also assessed for cross-processing herring with lingonberry pomace. The environmental performance of the resulting protein ingredients were assessed on a mass and delivered protein basis. Potential environmental impacts for climate change, energy consumption, land occupation, and depletion of marine resources were addressed. No ingredient performed better in all environmental impact categories, but delaying the helper addition had the most significant influence in reducing the product's environmental impacts. This study's outcomes enable analysts to direct research towards the most relevant parameters for producing a protein ingredient with lower environmental impact.

1. Introduction

Food production and consumption are important contributors to environmental degradation worldwide (Cucurachi et al., 2019). Our food systems' share of anthropogenic greenhouse gas emissions is estimated to be between 19 % to 37 % (Crippa et al., 2021; Poore and Nemecek, 2018; Rosenzweig et al., 2020; Vermeulen et al., 2012). Agrifood systems consume about 30 % of the world's energy (IRENA and FAO, 2021). In terms of area, food production accounts for approximately 43 % of the world's ice- and desert-free land (Poore and Nemecek, 2018), with agriculture being responsible for 80 % of the worldwide deforestation (Kissinger et al., 2012). In the case of marine-sourced foods, fish stock overexploitation is a topic of great concern, and Sustainable Development Goal 14 within the 2030 Agenda for Sustainable Development set a target to effectively regulate harvesting, end overfishing, and restore depleted fish stocks (United Nations, 2015).

Several approaches are being used to tackle the need to deliver food to the world population while minimizing the environmental problems associated with food production and consumption. One of these approaches is the valorization of food industry side streams. Here, the term *side stream* is defined as the non-primary output of food processing, regardless of its use, and *co-products* are the non-primary outputs destined for human consumption. Side streams of the food industry are characterized by their high proportion of organic material (Russ and Meyer-Pittroff, 2004). Food processing side streams, such as fruit pomace from juice pressing (Albuquerque et al., 2016), non-fillet part of fish (Hemker et al., 2020), vegetable stalks (Ferreira et al., 2018), brewers spent grains (Heredia-Sandoval et al., 2020) contain nutritionally valuable compounds, such as high-quality proteins, phenolics, vitamins, and minerals. An increasing interest in the use of side streams as raw materials was revealed by a recent literature review that identified over 150 articles exploring the bioactive compounds of agro-industrial side streams, with a relatively steady increase in the number of publications in the recent years (Reguengo et al., 2022).

During the past 20 years, the idea of pH-shift processing has been recognized as a promising approach for extracting proteins from fish and fish co-products (Abdollahi et al., 2020; Chen and Jaczynski, 2007; Marmon and Undeland, 2010; Nguyen et al., 2022; Undeland et al., 2002). Abdollahi et al. (2020) investigated the production of protein ingredients by cross-processing fish co-products with antioxidant-rich materials, referred to as helpers. The authors published results of the total protein yield, lipid oxidative stability, visual appearance of the pro-

* Corresponding author at: Chalmers University of Technology, Department of Technology Management and Economics, SE-412 96 Gothenburg, Sweden.

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tein isolate with the precipitation effect of helpers in cross-processing also being recorded. Promising results for the improved oxidative stability of the protein isolates when cross-processing herring co-products with lingonberry (*Vaccinum vitis-idaea*) pomace, apple (*Malus domestica*) pomace, brown seaweed (*Saccharina latissima*), or green seaweed (*Ulva fenestrata*) have been recently demonstrated (Zhang et al., 2022a). Further studies reported that the cross-processing of herring co-products with lingonberry press-cake or green seaweed significantly increased the water solubility and emulsification activity of the produced protein isolates; and the addition of lingonberry press-cake was found to also improve gel-forming capacity (Zhang et al., 2023).

Regarding the safety of isolates, versions of the pH-shift technique have already been used in food industry since the 1950s for different raw materials (Vogel and Mohler, 1959), and as stressed by Nolsøe and Undeland (2009), alkali-produced protein isolates have a generally regarded as safe (GRAS) status (FDA, 2004). The fish and helper side streams must be treated in a food-grade way, according to fundamental operational and environmental requirements necessary to manufacture safe foods (Hayes, 2018). Also, a commissioned third-party evaluation on the characteristics of the isolate produced with fish side streams concluded that the pH-shift process does not cause significant changes in the composition or structure of fish protein isolate and would not affect its nutritional value, metabolism, or level of undesirable substances in a way that would warrant regulatory concerns.

The valorization of food industry side streams introduces additional material processing steps, and it is essential to consider the quality and quantity of materials available to promote industrial symbiosis in the food industry (Mirabella et al., 2014). In terms of the cross-processing raw materials investigated by Zhang et al. (2022), Sweden's estimated annual generation of herring heads and backbones is around 3600 tonnes (Coelho et al., 2023), making these side streams a potential candidate for valorization into a protein ingredient. For the helpers, lingonberry and apple pomace are available in Sweden, with estimated quantities of 140 tonnes for lingonberry pomace (Coelho et al., 2023) and 500 tonnes of apple pomace per year, based on data from six juice producers in the south of Sweden (Jönsson, 2010). Seaweed production in cold and temperate climates has been reported to be on the rise (FAO, 2020), and a feasibility study shows that seaweed farming has the potential to become a profitable industry in Sweden (Hasselström et al., 2020).

Life cycle assessment (LCA) is a tool for making holistic comparisons among possible or competing systems, as well as for optimizing an existing system (Curran, 2017). It is a compilation and evaluation of a product system's inputs, outputs, and potential environmental impacts throughout its life cycle (ISO, 2006a). Through its quantitative approach, LCA can identify potential trade-offs between comparable products, occurring when impacts are shifted from one life cycle stage to another or when the reduction of one type of environmental impact comes at the cost of another impact (Cucurachi et al., 2019; Yang et al., 2012).

In a previous study, Coelho et al. (2023) carried out an LCA of a protein ingredient derived from cross-processing herring heads and backbones together with lingonberry pomace, and its ultimate use in a fish ball consumer product. The authors compared the environmental impact of this fish ball with a benchmark fish ball, and with salmon fillets as an alternative benchmark. The fish ball made with the protein ingredient performed well in relation to the benchmark food products. The impacts of climate change and energy consumption for the fish ball were dominated by the herring and lingonberry inputs, the authors suggested a reduced helper input as an improvement opportunity for the environmental profile of the protein ingredient (Coelho et al., 2023).

In this paper, we use LCA to measure the impacts of producing a protein ingredient through cross-processing herring and a helper raw material, building on the study of Coelho et al. (2023). Here we investigate cross-processing of herring side streams with the four different helpers identified as the most promising in the work of Zhang et al. (2022a), as well as the reduction of addition ratio and a modified version of the cross-processing technique.

2. Material and methods

LCA is an iterative process that consists of: the definition of the goal and scope of the study, collection of relevant data on material and energy flows (life cycle inventory), characterization of the potential impacts (life cycle impact assessment), and interpretation of results (ISO, 2006a, 2006b).

2.1. LCA goal and scope

2.1.1. Product systems general description

2.1.1.1. Cross-processing, classic and precipitation technique. The cross-processing assessed here starts with the homogenization of fish co-products in water, followed by the pH-driven protein solubilization at high pH e.g., pH 11.5, using the addition of NaOH through a stirring process. At laboratory scale, a centrifuge separates the soluble protein layer from the lipid emulsion and solid residue layer. The soluble protein layer is subjected to a second stirring process where HCl is added to the soluble protein layer bringing the pH to 5.5 for protein precipitation. A second centrifugation process separates the protein from the water. For the context of this paper, this process is referred to as the classic method or technique. At industrial scale, the separation is carried out by a three and two phase decanter (Coelho et al., 2023). A schematic representation of these processes investigated is presented in Fig. 1(a). With the aim of increasing yield by reducing the losses of helper during the first decanting step, we assessed the environmental impacts of the process where the helper is added *after* the first decanting step. The delayed helper addition requires an additional homogenization before adding the acid, followed by steps identical to those of the classic method. This processing technique version will be called precipitation method or technique, illustrated in Fig. 1(b).

2.1.2. Goal

The primary goal of this study was to investigate the influence that the use of different helpers, cross-processing techniques and different helper additions have on the environmental profile of a protein ingredient obtained by cross-processing herring with a helper. This study is intended to contribute to the development and improvement of a protein ingredient derived from fish co-products that are currently not destined for human consumption with the objective of increasing the conservation of resources. By investigating a range of alternatives, this study has the ambition to provide guidance on which parameters are the most relevant in order to deliver a protein ingredient with potentially less environmental impact. Considered as cornerstone scenarios, these alternatives provide an assessment of the range of the scale of potential impacts of cross-processing the herring sidestreams, which can be compared with other benchmarks.

2.1.3. Functional unit

The functional unit is a quantified description of the function of a product, and is the reference basis for all calculations regarding impact assessment (Weidema et al., 2004). The functional unit investigated here is "the provision of 1 kg of protein ingredient, obtained from cross-processing herring heads and backbones and one helper, through pH-shift processing, in Sweden", with the protein ingredient being further destined for preparation into a food product. As different helpers, techniques and addition ratios influence the protein yield to different extents, the results are also presented on a protein basis. Therefore "100 g of protein delivery" is also used as the basis for the comparison among the output products.

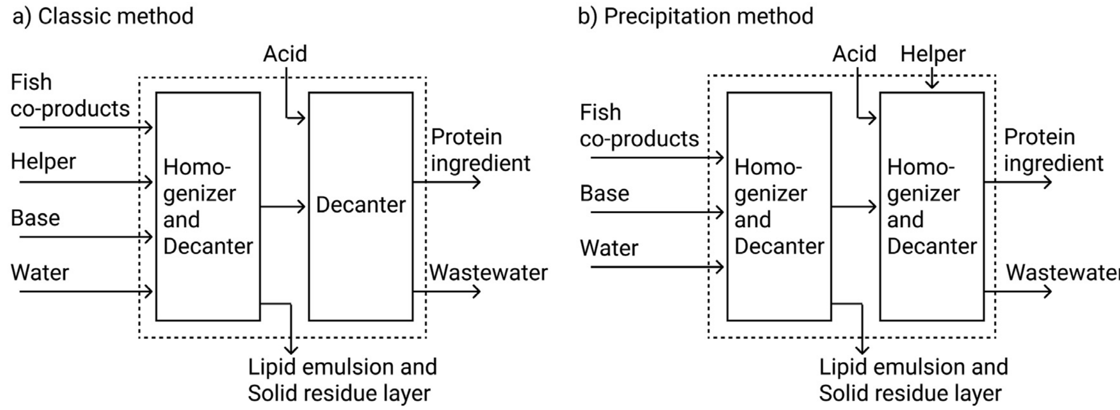

Figure 1. Diagram of the cross-process showing the material inputs to a) the classic cross-processing and b) the precipitation technique or method in which the helper addition is delayed.

2.1.4. Type of LCA and scenarios

The study is a comparative LCA, in which a comparison between a protein ingredient obtained from cross-processing herring heads and backbones with different helpers. Here we investigate four helper scenarios namely lingonberry pomace, apple pomace, brown seaweed, and green seaweed. The addition ratio for the helpers was chosen so that 30% of the helper-fish mixture consisted of a helper on a dry-weight basis (d.w.). We also investigated a lower addition ratio scenario (10 % d.w.) motivated by a previous study on cross-processing herring which lingonberry found that lingonberry contributed 40 % of the climate change impact and cumulative energy consumption (Coelho et al., 2023). Motivated by the desire to investigate the influence of the processing method, a precipitation technique scenario was assessed for herring and lingonberry case combination, for 30 % and 10 % addition ratios.

2.1.5. System boundaries and assumptions

The study system's boundary is "cradle-to-gate", meaning that it includes impacts associated with the extraction of raw material, transport, and processing into a protein ingredient, with process wastewater treatment also included as part of the product system (Fig. 2). Inputs of energy, herring co-products, and helper are considered as part of the foreground systems for which system-specific primary data is collected. Material and energy flows associated with the production of the inputs, energy, and the treatment of wastewater are considered as part of the background system. We modeled the process at an industrial scale with the raw materials modeled as being produced and processed in Sweden. On account of the location of relevant upscaled processes, the cross-processing site was assumed to take place in Uddevalla, in western Sweden.

2.1.6. Data sources and software

We used ecoinvent database version 3.7 with cut-off allocation (Wernet et al., 2016) for the background data. For seaweed production and apple juice, we used Agribalyse 3.0.1 dataset (ADEME, 2020), adapting it to represent the Swedish case. Herring fishing and processing, lingonberry juice processing, and upscaling of the cross-process, were modeled in the same way as in Coelho et al., (2023). For fisheries, a discard rate of 4.7 % based on purse seine fishing gear discard rates from Pérez Roda et al. (2019), following Coelho et al. (2023) was also accounted for. The LCA was modeled using the software OpenLCA 1.10.3.

2.1.7. Allocation

Mass allocation was applied to herring co-products and pomace, following the allocation priority ranking of ISO 14044 (ISO, 2006b). For the cross-process, even though the fat emulsion and solid residues generated can potentially be valorized, the cross-process was not considered as a multi-output process on account of large uncertainties associated with adding such processes, i.e., all environmental burdens are associated with the protein ingredient, meaning that no allocation is applied for this life cycle stage.

2.1.8. Life cycle impact categories

In life cycle assessment, the elementary flows associated with the product system (e.g. energy, and material flows) are then translated into impacts using scientific models of cause-effect chains (Tillman and Baumann, 2004). More specifically, in the impact assessment, the collected elementary flow (e.g. CH_4 emissions) are multiplied by their respective characterization factor (e.g., kg CO_{2eq}/kg CH_4). The environmental impact categories selected for the study were determined according to the goal and scope (ISO, 2006b). Reflecting the concerns mentioned in the introduction and the objective of resource conservation, we selected four environmental impact categories to represent climate change, energy consumption, land use, and impacts on marine biotic resources. We selected climate change (CC) due to the significant amount of greenhouse gases emitted by food systems, we assess this category using IPCC's 2013 using radiative forcing as Global Warming Potential (GWP100) in CO_{2eq}. To address concerns regarding energy use and the equitable availability of current energy resources, we used cumulative energy demand (CED) of fossil resources in MJ. This indicator can also be interpreted as a measure of fossil resource depletion which is a matter of intergenerational equity. Given the direct link between food systems and the overexploitation of terrestrial and marine resources, we assessed these impacts using land occupation in m^2•year, and to represent marine biodiversity we used depleted stock fraction (I_{DSF}) (dimensionless) using the impact characterization factors developed by Hélias et al. (2018).

3. Life cycle inventory

Data relating to cross-processing herring side streams with a 30 % addition of lingonberry via the classic method were based on published values (Coelho et al., 2023). For apple, brown seaweed, and green seaweed, the amount of helpers and output product is based on the dry weight ratios for each combination based on the work published by Zhang et al. (2022a). For the addition ratio and technique scenarios, the input and protein ingredient output values are based on primary data from our own laboratory measurements (unpublished). Values for the acid, base, and the outputs of the first centrifuge, are our own laboratory measurements for all combinations, except for outputs of the first centrifuge for the lingonberry 30 % addition via the classic method, which were estimated based on a mass balance and calculated proportionally

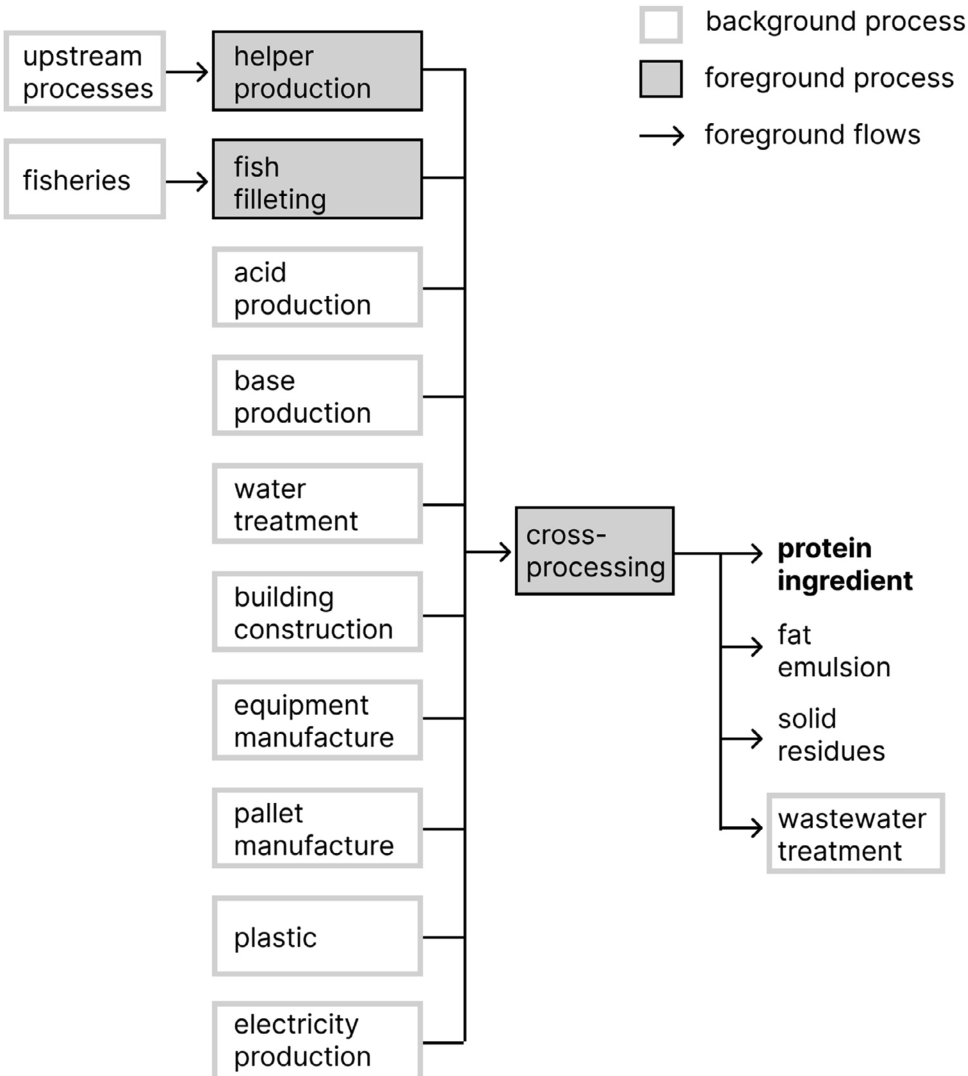

Figure 2. Flow chart of the system boundaries of product system. In the case of the pomace "helper production" refers to juice processing of the lingonberry and apple generating pomace, for the seaweeds it refers to the seaweed cultivation.

based on the values for the lingonberry 10 % classic method. The intermediate flows and outputs to wastewater treatment are derived from mass balances. The list of the raw material inputs and protein ingredient output with a moisture content of 80 % for the different scenarios investigated are presented in Table 1. The protein content of the protein ingredients is presented in Table 2.

3.1. Helpers

3.1.1. Lingonberry pomace

Lingonberry pomace was modeled as a co-product of Swedish lingonberries processed into juice. We modeled this system in the same manner as a previous study by Coelho et al. (2023), except for the transport of the lingonberry pickers. For lingonberry pickers, we modeled 80 % of the workforce as coming from Thailand and the remaining 20 % from Europe (Johnn Andersson, personal communication), as these values are understood to be more representative of the current practices. We modeled a vehicle occupancy of four people per vehicle and adapted the fuel consumption and emission for a large passenger car, emission standards EURO 4, assuming 70 kg per person.

3.1.2. Apple pomace

Apple pomace was modeled as a co-product generated from the production of juice from Swedish apples to keep the geographical scope consistent to the lingonberry case. Life cycle inventory data for apple production from ecoinvent was used. As ecoinvent does not have data for Sweden, the data set selected from ecoinvent is denominated "rest of the world" (RoW).

Apples are harvested for about four months a year, are stored whole at cool temperatures, and processed 9 to 10 months per year (Martin Golbe, personal communication). We modeled a maximum storage of 10 months, meaning that the maximum stored amount of apples would be 60 % of the total processed apples in a year. To calculate the storage area and amount of crates, we used whole apples' bulk density of 450 kg/m^3 (Hazbavi, 2014). Apples were modeled as stored in bulk wood crates of 1200 × 1000 × 800 mm, and we calculated that 2.74 crates are required per tonne of apple. The crates are constructed of spruce and pine on a standard pallet, with a total weight of 80 kg. Inventory data for the wood pallet was used from ecoinvent, with the addition of 55 kg of softwood and 0.2 kg of steel for nails per wood box, also from ecoinvent. The crates' lifetime was modeled as the expected lifetime of wooden pallets. Wood pallet lifetime was expected to be ten years (Deviatkin et al., 2019), with one use per year. Considering the crate volume, the potential to stack four crates vertically, and a 4-meter ceiling, we calculated a storage volume of 3.95 m^3 to store 1 tonne of apples. The chilling effort is then calculated using the value of 35 kWh/m^3/y (Evans et al., 2015), resulting in electricity consumption of 138 kWh/t apple stored.

The apple juice processing is modeled using Agribalyse inventory for industrial apple juice production, using mass allocation, and with the electricity mix modified to represent the Swedish case. The juice processing facility was assumed to be located nearby the orchards. Therefore, a distance of 50 km was modeled, representing the transport from

Table 1
Raw material inputs as fresh weight (fw), intermediate flows and, output flows for the different combinations and methods investigated. Values of herring, helper, water, and output protein ingredient are sourced from (1) Coelho et al. (2023), (2) Zhang et al. (2022a), (3) own measurements. Acid and base values are own measurements. Outputs of the 1st centrifuge are own measurements except for lingonberry 30 % for which the value was obtained through mass balance.

Helper	Lingonberry(1)	Apple(2)	Brown seaweed(2)	Green seaweed(2)	Lingonberry(3)		
Processing technique version			Classic		Classic	Precipitation	Precipitation
Helper addition ratio			**30%**		**10%**	**30%**	**10%**
Process step							
1st homogenization							
herring (g)	100	100	100	100	100	100	100
helper (g)	36.0	39.6	43.0	42.6	10.4	n.a	n.a
water (g)	764	838	858	856	662	600	600
total inputs to be homogenized (1st)	900	977	1001	998	772	700	700
1st stirring (base addition)							
1st homogenate (g)	900	977	1001	998	772	700	700
NaOH (g)	16.8	28.4	19.0	21.4	12.0	12.0	12.0
total inputs to be stirred (1st)	917	1006	1020	1020	784	712	712
1st centrifuge [a]							
Inputs (g)	917	1006	1020	1020	784	712	712
Fat emulsion and solid residue layer (g)	234.7	292	261	154	254	100	100
2nd homogenization							
soluble protein layer (g)	n.a	n.a	n.a	n.a	n.a	612	612
helper (g)	n.a	n.a	n.a	n.a	n.a	34.8	11.6
total inputs to be homogenized (2nd)	n.a	n.a	n.a	n.a	n.a	647	624
2nd stirring (acid addition)							
2nd homogenate (g)	682	714	759	866	530	647	624
HCl (g)	13.6	22.4	15.6	20.2	10.4	3.3	6.5
total inputs to 2nd stirrer and 2nd centrifuge [a] (g)	696	736	775	886	541	650	630
Outputs							
protein ingredient [b] (g)	40.0	41.4	37.0	53.2	33.9	92.0	60.0
effluents to wastewater treatment (g)	656	695	738	833	507	558	570

[a] A batch centrifuge was used at laboratory scale and at industrial scale is modeled as a three and two phase decanter for the first and second centrifugation, respectively.
[b] The protein ingredient had a moisture content of approximately 80%.

Table 2
Protein content in g/100 g on the dry weight with data showing mean values ± standard deviation ($n \geq 2$). Data sources are (1) own measurements, referring to the same experiments used in Coelho et al. (2023), (2) Zhang et al. 2022, and (3) own measurements.

Helper	Lingonberry(1)	Apple(2)	Brown seaweed(2)	Green seaweed(2)	Lingonberry(3)		
Processing technique version			Classic		Classic	Precipitation	Precipitation
Helper addition ratio			30%		10%	30%	10%
Protein content (g/100 g)	72.42 ± 0.23	68.72 ± 0.04	73.80 ± 0.84	72.74 ± 0.15	68.62 ± 1.04	50.43 ± 0.90	64.37 ± 1.58

the orchard to the storage and juice processing site, using a 16-32 EURO 6 truck, following the truck type used in Agribalyse. In Sweden, about 90 % of apple trees are located in the county of Skåne (Persson, 2012), particularly in the region of Österlen (Kiviks Musteri, 2022). The pomace was modeled as being transported by refrigerated truck for 400 km to reach Uddevalla. We used bulk a density value of 850 kg/m^3 for industrial pomace (Kenney et al., 1999), moisture content of 82 % (Zhang et al., 2022a), and an apple juice production for ten months a year to calculate the volume to be stored.

3.1.3. Seaweed

Seaweed production was modeled by adapting Agribalyse's seaweed model, changing the electricity mix to Sweden and modified the seaweed harvested yield to represent the Swedish conditions. An output of fresh seaweed of 8 tonne/km of long line (Hasselström et al., 2020) was used for brown seaweed (*Saccharina latissima*). For fresh green seaweed (*Ulva fenestrata*), the productivity of 1.2 tonne/km of long line was used (Steinhagen et al., 2022). For the location, we considered production in the Koster Archipelago (Hasselström et al., 2020; Steinhagen et al., 2022) and that the seaweed is then transported 100 km on a refrigerated truck to Uddevalla. We modeled the seaweed harvesting over five months in a year on the basis of the harvesting season for *Saccharina latissima* (Ocean Rainforest, 2022). The moisture content of green and brown seaweed was approximately 82 g/100 g (Zhang et al., 2022a). Interpolating the bulk seaweed density values of 70 and 90 g/100g provided in Sappati et al. (2019), the bulk density was calculated as 1000.8 kg/m^3.

3.2. Storage

The helpers and herring co-products were modeled as stored in 210-liter HDPE barrels of 9 kg each, used five times, with four barrels stored on an EU-flat pallet. Pallets were assumed to be used ten times. Both HDPE and EU-flat pallet inventory data were taken from ecoinvent. The chilling effort for frozen storage was calculated using the value of 66 kWh/m^3/y (Evans et al., 2015).

3.3. CROSS processing

All raw materials except apple pomace are minced before homogenization using a grinder with a 4.5 mm hole plate (Zhang et al., 2022a). All subsequent steps follow the modeling of Coelho et al., (2023) with the addition of wastewater treatment of the process water, which was previously omitted.

When modeling the upscaled system, Coelho et al. (2023) considered the limiting Swedish side stream of lingonberry pomace and modeled a scaled up system that handles an annual input flow of 378 tonnes of herring co-products and helper. We kept the scale of the processes constant

Table 3
Input materials, storage, equipment, and energy, and output flows for the cross-processing of the different scenarios. Values refer to 1 kg of output protein ingredient with approximately 80% of moisture content.

Helper	Lingonberry	Apple	Brown seaweed	Green seaweed	Lingonberry		
Processing technique version	Classic				Classic	Precipitation	Precipitation
Helper addition ratio	30%				10%	30%	10%
Material and energy inputs							
Material inputs							
herring (kg)	2.5	2.4	2.7	1.9	2.9	1.1	1.7
helper (kg)	0.9	1.0	1.2	0.8	0.3	0.4	0.2
water (kg)	19.1	20.2	23.2	16.1	19.5	6.5	10.0
NaOH (kg)	0.4	0.7	0.5	0.4	0.4	0.1	0.2
HCl (kg)	0.3	0.5	0.4	0.4	0.3	0.04	0.1
Infrastructure and storage material							
area (m^2)	5.23×10^{-4}	4.6×10^{-4}	5.9×10^{-4}	4.1×10^{-4}	5.0×10^{-4}	2.3×10^{-4}	2.9×10^{-4}
EU-flat pallet (unit)	2.79×10^{-4}	2.1×10^{-4}	3.1×10^{-4}	2.1×10^{-4}	2.7×10^{-4}	1.2×10^{-4}	1.5×10^{-4}
equipment, steel (kg)	5.12×10^{-3}	5.1×10^{-3}	5.8×10^{-3}	4.0×10^{-3}	4.9×10^{-3}	2.2×10^{-3}	2.8×10^{-3}
Processing electricity							
electricity, grinding, fish (kWh)	4.00×10^{-2}	3.9×10^{-2}	4.3×10^{-2}	3.0×10^{-2}	4.7×10^{-2}	1.7×10^{-2}	2.7×10^{-2}
electricity, grinding, helper (kWh)	1.44×10^{-2}	1.5×10^{-2}	1.9×10^{-2}	1.3×10^{-2}	4.9×10^{-3}	6.1×10^{-3}	3.1×10^{-3}
plastic drums for storage (kg)	2.01×10^{-2}	1.5×10^{-2}	2.2×10^{-2}	1.5×10^{-2}	1.9×10^{-2}	8.7×10^{-3}	1.1×10^{-2}
temperature control (kWh)	$3.03 \times 10^{+0}$	$2.6 \times 10^{+0}$	$3.4 \times 10^{+0}$	$2.3 \times 10^{+0}$	$2.9 \times 10^{+0}$	$1.3 \times 10^{+0}$	$1.7 \times 10^{+0}$
1^{st} homogenization (kWh)	5.68×10^{-3}	6.0×10^{-3}	6.8×10^{-3}	4.7×10^{-3}	5.7×10^{-3}	1.9×10^{-3}	2.9×10^{-3}
1^{st} stirring (kWh)	6.88×10^{-5}	7.3×10^{-5}	8.3×10^{-5}	5.8×10^{-5}	6.9×10^{-5}	2.3×10^{-5}	3.6×10^{-5}
1^{st} decanter (kWh)	5.62×10^{-2}	5.6×10^{-2}	6.4×10^{-2}	4.4×10^{-2}	5.4×10^{-2}	2.4×10^{-2}	3.1×10^{-2}
2^{nd} homogenization (kWh)	n.a	n.a	n.a	n.a	n.a	1.8×10^{-3}	2.6×10^{-3}
2^{nd} stirring (kWh)	5.22×10^{-5}	5.3×10^{-5}	6.3×10^{-5}	4.8×10^{-5}	4.7×10^{-5}	2.1×10^{-5}	3.1×10^{-5}
2^{nd} decanter (kWh)	7.95×10^{-2}	7.9×10^{-2}	9.0×10^{-2}	6.3×10^{-2}	7.6×10^{-2}	3.4×10^{-2}	4.3×10^{-2}
Outputs							
water to wastewater treatment (liters)	16.4	14.9	16.8	19.9	15.7	6.1	9.5

and the same as the case presented in Coelho et al. (2023). More specifically, these were modeled as being processed in a 500 L stirrer and a 1000 L homogenizer at industrial scale, with their energy consumption based on Piccinno et al. (2016). Energy for grinding represents the worst case, also following the same source. Decanting processes at industrial scale, as well as infrastructure requirements were based on those presented in Coelho et al. (2023).

4. Results

4.1. Input and output flows

A compilation of the raw materials, different equipment needs, and the energy input for the different processing steps and storage are presented in Table 3.

4.2. Life cycle impact assessment: Helper comparison scenarios

The life cycle impact assessment results for the different helpers are presented in Fig. 3, both on a mass and protein basis communicating the results for each functional unit. For CC and CED, most of the impacts of the protein ingredient are associated with herring co-products and helper, with infrastructure, electricity, water, acid, base, and storage equipment accounting for less 25 % of the impacts for all the ingredients. For LO, fish and helper inputs accounted for 80 % for the ingredient produced with apple pomace, 57 % for the impacts of ingredients produced with lingonberry, 48 % for the green seaweed protein ingredient and 41 % for brown seaweed.

For CC and CED, the protein ingredient that had the lowest potential environmental impact was the one produced using apple pomace, with the helper accounting for 13 % of the impact of CC. For the ingredient produced with brown seaweed, the helper production accounted for 19 % of the impact for these two categories. For these two categories, the protein ingredient with the highest potential impact both on a mass or protein basis was the one produced using a green seaweed helper, with the green seaweed production accounting for 60 % of CC and CED impacts.

For land occupation, the protein product produced with apple pomace had the highest impact. The production of apples accounts for 57 % of the land occupation impact for the protein ingredient made with apple pomace. The land occupation associated with the ingredient produced with apple pomace was double the land occupation of the protein ingredient produced with lingonberry, which was the protein ingredient presenting the second highest land occupation.

For the impact on marine resources depletion, the ingredient produced with green seaweed presented the lowest impact in comparison to the other helpers both for the mass and for the protein basis functional unit. For both functional units, the impact to depleted stock fraction of the ingredient produced with green seaweed was about 30 % the impact of the ingredient produced with brown seaweed, which was the highest. Using lingonberry or apple pomace resulted in similar values to that of brown seaweed.

4.2.1. Life cycle impact assessment: Addition ratio and technique version

The impact assessment results for the comparison of the different addition ratios and precipitation technique scenarios are presented in Fig. 4. For both functional units, the precipitation method resulted in lower potential environmental impacts than the classic method for all impact categories. For CC, CED, and LO impact categories, a lower helper addition ratio resulted in potentially less environmental impacts on the protein basis.

Using the precipitation method results in a potential emission of 1.1 and 1.3 kg CO_{2eq}/kg of protein ingredient for 30 % and 10 % lingonberry addition, respectively. These values are about half of the values obtained for lingonberry 30 % addition using the classic method.

For the marine resources depletion impact category, measured here using the impact of the depleted stock fraction, the protein ingredient produced with 30 % lingonberry via the precipitation method had the least impact. Compared to the protein ingredient with the same addition ratio but produced with the classic method, the precipitation technique results in a 56 % reduction in the potential impact on marine resources on a mass basis. Using the precipitation technique to process lingonberry with 10 % addition resulted in a 43 % reduction of impacts in this category when assessed on a mass basis. On a protein basis, the

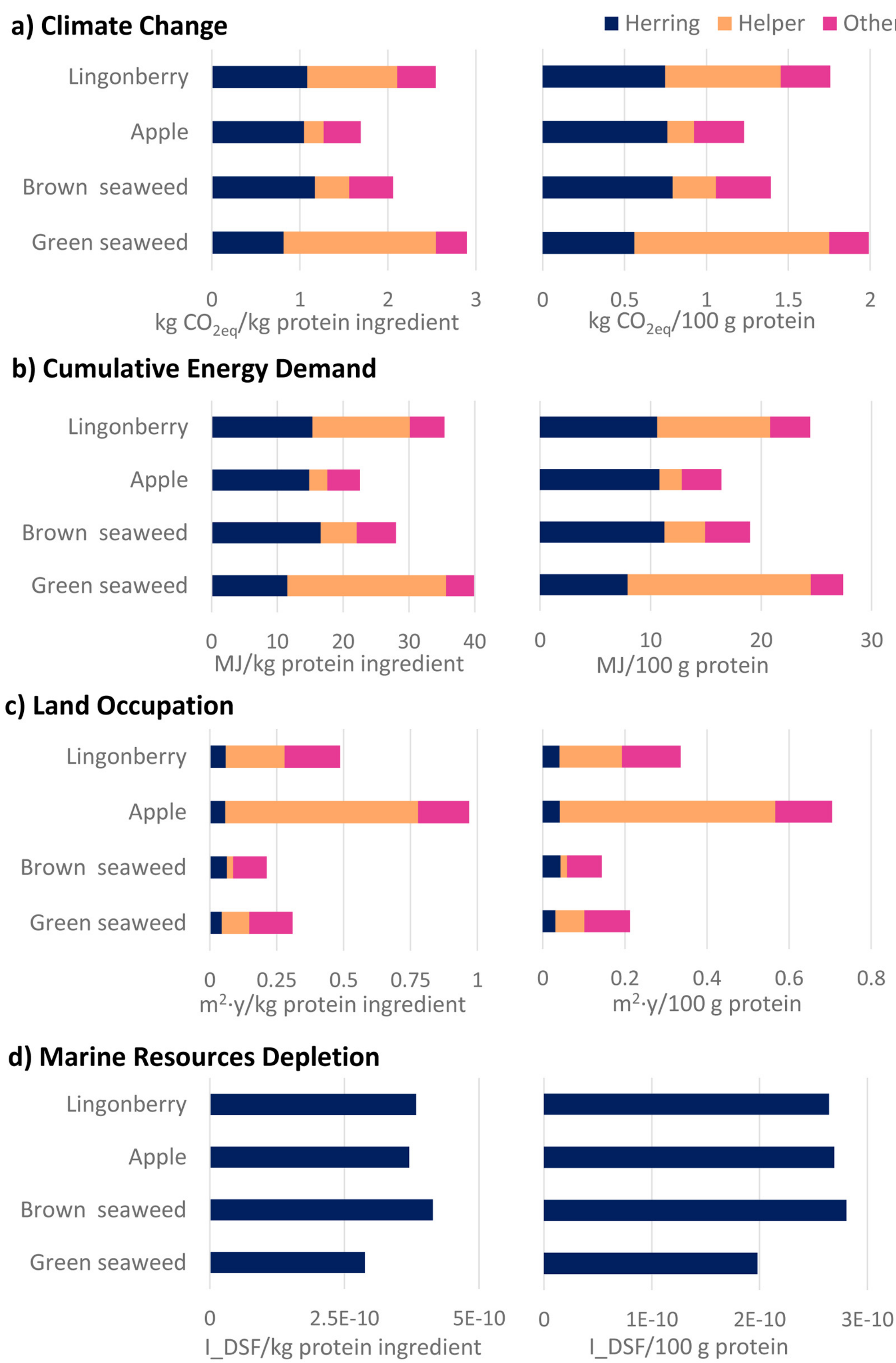

Figure 3. Impact assessment results for different protein ingredients for the helper scenarios. The ingredients are generated via classic technique with a helper addition ratio of 30 % on a dry weight basis. Results on a mass basis are presented in the left column (per kg of protein ingredient), and on a protein basis shown on the right column (per 100g of protein), for a) climate change, b) cumulative energy demand, c) land occupation, and d) marine resource depletion, where I_DSF is impact of depleted stock fraction.

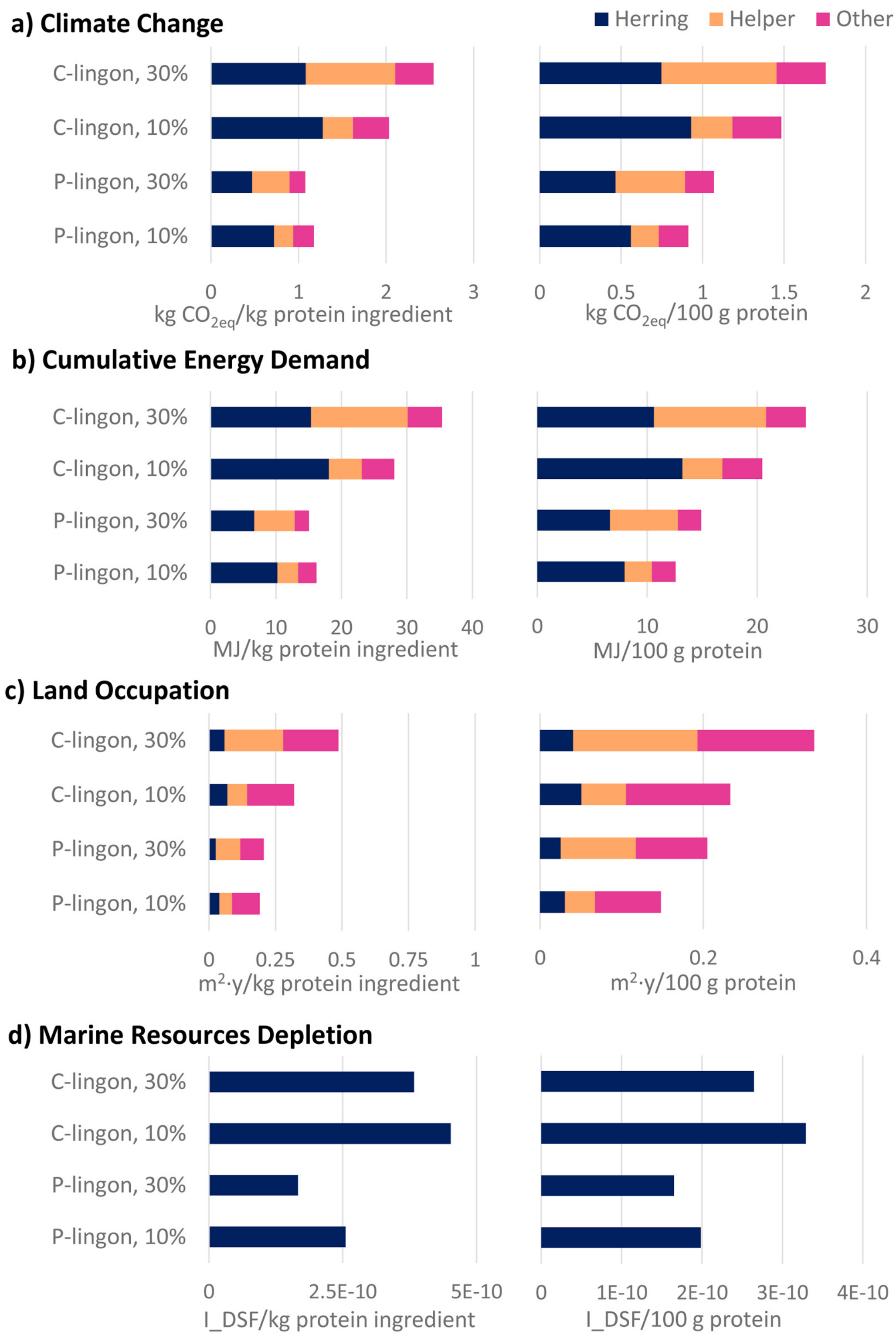

Figure 4. Impact assessment results for the addition ratio and technique scenario for the lingonberry (lingon) addition ratio (30 % and 10 %) for the classic (C) and precipitation technique (P). Results on a mass basis are presented in the left column (per kg of protein ingredient), and on a protein basis shown on the right column (per 100g of protein), for a) climate change, b) cumulative energy demand, c) land occupation, and d) marine resource depletion, where I_DSF is impact of depleted stock fraction.

depleted stock fraction impact was about 40 % less when using precipitation method for both addition ratios of lingonberry pomace.

5. Discussion

An important aspect identified when assessing the helper scenarios was the identification of impact category burden shifting. In this study, we found that using apple pomace, which is a helper with a lower contribution to climate change and energy consumption than lingonberry pomace, results in a protein ingredient with a much greater impact associated with land occupation. This overall result was expected given that the other helpers, namely seaweed and lingonberry, demand very little area compared to a horticultural product. As lingonberries modeled here are harvested from wild ecosystems this land is not considered occupied. Our results show the importance of quantifying impacts not only through the supply chain but also relating to relevant impact categories beyond climate change. The results can also enable decision makers to consider their environmental performance priorities. For example, for the classic technique, the lingonberry land impacts are about half those of the apple helper, but the climate change impacts of the ingredient made with apple pomace are about two-thirds of that made with lingonberry pomace. So, considering these two indicators alone, if the decision maker values climate change at least 50% higher than land occupation, their choice would be to choose apple pomace as a helper.

By performing an LCA we are able to share more holistic information with the process development team about the various potential impacts of the product under development and their underlying causes. More specifically, despite lingonberry being harvested from the wild, its impact is larger because harvesting workforce travels from Europe and Asia to Sweden for this exclusive purpose. The transport of the berry picking workforce to Sweden has previously been identified as a significant contribution to the life cycle of lingonberry fruits (Sjons, 2016). This study shows that despite apples being cultivated, using apple pomace produces a protein ingredient with potentially lesser impacts in terms of climate change and energy consumption than the protein ingredients made with lingonberry pomace and seaweed through the classic method.

As the level of protein in the finished protein ingredient varies depending on the helper used, calculating the environmental impacts on a protein basis is also relevant. This aspect was captured by LCA, showing the potential importance of the functional unit which allows the results to be presented on a different basis, here mass and protein. Nevertheless, using a protein basis to select a helper for producing an ingredient does not affect the outcome of selection of the environmentally preferable helper. Among the different helpers, the best performance was dependent on the category being evaluated, more specifically, apple for climate change and cumulative energy demand, brown seaweed for land occupation, and green seaweed for marine resources depletion.

5.1. Precipitation technique

Innovations in food systems have been widely recognized as having a critical role in the fight against climate change (Tubiello et al., 2021). The protein ingredients produced with the precipitation technique version presented reduced potential environmental impacts for all categories despite generating lower yields of protein ingredients. This is one example of when LCA results are not always intuitive, as here, neither the product yield nor the protein content alone can capture which technique is most beneficial.

The potential environmental benefits of the precipitation technique are primarily due to the helper not being lost during the first centrifugation. When delaying lipid oxidation by adding the lingonberry pomace after the first centrifugation, the helper remains in the final protein isolates, therefore increasing the yield of the protein ingredient but diluting its protein content. The protein content of lingonberry pomace is 5.57 g/ 100 g on a (d.w.), and herring heads and backbones contain 48 g protein/g 100 g (d.w.) (Zhang et al., 2022a). The protein content for ingredients produced via the precipitation method was more than two times the yield of a protein ingredient produced with the higher helper addition ratio (lingonberry pomace at 30 % addition), but the protein content yield was only 30 % less. For the lower helper addition ratio (lingonberry pomace at 10 % addition), the protein content was 1.75 times higher when produced via precipitation, but the protein content was only 6 % less when compared to its production through the classic method. As the impacts are presented in relation to the mass as well as for the protein delivered, the protein ingredient results in less impacts per functional unit.

If aiming for a product with higher protein content, the protein yield reduction resulting from the use of the precipitation technique can be compensated by subsequently removing the helpers, which is feasible and convenient. The helper was observed to be partially separated at the bottom from the protein-rich phase when centrifugation (8 500 $\times$ g, 20 min, 4°C) was applied following the precipitation step. By simply optimizing the centrifugation conditions (speed and time), helpers can be removed completely. The environmental impacts associated with this compensatory technique have not been investigated in the study at hand. However, considering that the energy needed for cooling storage and assessed processing facilities is two orders of magnitude larger than either of the centrifugation steps already assessed, and energy consumption in the process matters less than the production of the ingredients, we expect that the addition of this step would not affect the ranking of alternatives. However, we note that the removal may not be desirable since the helper provides important antioxidants which helps protect the precipitate from lipid oxidation during extended storage, and the helper can also provide, e.g., fibers and vitamins to the precipitate.

When developing a new food product or ingredient, the focus is on aspects such as storage stability, sensorial attributes, techno-functional properties, and nutritional value that must be verified alongside material inputs and outputs that are part of the environmental assessment. The LCA results bring to light an interesting research opportunity to promote the investigation of the precipitation method. We thus suggest laboratory trials of apple and seaweed helper addition via the precipitation method to verify product stability as, based on the results for the lingonberry case, this technique presents a potential for further reduction in environmental impacts.

Regarding other parameters variation in this processing technique, there is a reduced consumption of acid. For the lingonberry case at 30 % addition ratio, the amount of acid is reduced from 0.3 kg to 0.04 kg HCl/kg of output protein ingredient. This input, however, plays only a small role in the environmental impact of the protein ingredient, which is dominated by the input of herring and lingonberry itself. While minimization of acid and base consumption may be strived from a product-developed perspective, this study showed that the resulting environmental benefits of other interventions is greater.

5.2. Apple

Inventories for apple production in Sweden were not available in the databases used in this study. As creating the whole life cycle inventory of apple production in Sweden would be out of the scope of the project, we adjusted the logistics of apple production and storage to suit the local situation. In this study, we assessed apple pomace produced with apples cultivated in Sweden. We note that since pomace generated from imported apples is available, the origin of the apples may affect the results depending on the apple orchard yield and transport distances.

In modeling juice production mass allocation was used. Other approaches could have been used, such allocation on economic value, and would lead to a significantly lower environmental burden attributed to the apple pomace. We argue that mass allocation is suitable for exploratory studies such as this in which side stream prices may be affected by additional demand but is poorly predictable. Mass allocation is also consistent with the allocation preferences expressed in ISO14044. By applying mass allocation, the study at hand perceives apple pomace as raw material regardless of its current use or current economic value, but we acknowledge that other approaches may also be suitable.

5.3. Seaweed

We modeled the seaweed as being cultivated at sea, although the green seaweed actually used in the cross-processing experiments was derived from terrestrial tank cultivation. Life cycle inventory data availability was limited to sea cultivation for both green and brown seaweed in Sweden and commercial scale production potential of off-shore sea farm has been demonstrated in a recent study by Steinhagen et al. (2021). Ecosystems services have been identified in the production of seaweed, such as absorption of phosphorous, but also other aspects such as an alteration to the marine ecosystems. Impacts on biodiversity, food webs, and resilience depend on specific ecosystems, and specific farming practices have been previously investigated (Hasselström et al., 2018).

In this study we used data from Agribalyse, modifying the transport distances, seaweed production yield, and electricity grid mix to represent the Swedish case. We used a published value of 8 tonnes of wet weight per km of long line for brown seaweed, noting that this yield is slightly higher than the non-optimized seaweed production system modeled in Agribalyse. On the other hand, the yield used for green seaweed is representative of the best case in the literature and was only about 1 tonne of fresh weight per km of long line. Therefore, this study represents the best-case scenario for green seaweed when considering the yield values published in the literature for the Swedish case. The modeling of the two types of seaweed in this study can also be interpreted as representative of the range of different seaweed production systems regarding their yield.

Despite the higher protein ingredient yield and higher protein content, the protein ingredient made with green seaweed presented a lower environmental performance due to the low yield of the green seaweed production system, showing the importance of the seaweed yield to the protein ingredient environmental profile. Reducing the helper addition ratio can be particularly relevant for the case of green seaweed, a helper which had the highest contribution to the final impact of climate change and cumulative energy. For green seaweed, we stress that this raw material should not be ruled out as a potential candidate as a helper for further investigations despite having a worse performance. Instead, the investigation of lower addition ratios and, most importantly of precipitation method should be investigated with experimental trials. The seaweed protein content reported by Zhang (2022a) is 11.78 and 15.4 g/100 g (d.w) for brown and green seaweed, respectively, values which are two to three times the protein content of the lingonberry pomace. As previously explored in the discussion of the precipitation technique, the retention of the helper in the final product leads to increased yields and can compensate for diluted protein yield, resulting in reduced environmental impacts both for a mass and protein functional unit.

We modeled the protein product yield according to experimental results, but we point out that the protein content in the seaweed can vary with the season (Steinhagen et al., 2022) and this could further affect the final environmental footprint of the protein ingredient. We also note that there might be differences in the infrastructure required for the different seaweeds, and those have not been modeled here, e.g., if different anchoring systems are used, but we stress that the harvested yield is the factor that is the most relevant in this case.

5.4. Uncertainties

For comparative studies, uncertainty analysis can be performed by Monte Carlo sampling of the inputs' probability distributions (Igos et al., 2019). The results of this study relied on modeling herring co-products with different helpers, for which data regarding the energy and material consumption for its production was obtained from databases, literature, or a combination of both. Data relating to foreground systems, such as energy consumption for the cross-processing, the quantity of input materials, and transport distances, were modeled based on theoretical calculations or in the case e.g. of transport distance, based on assumptions. Because probability distribution functions were only available for ecoinvent data, applying Monte Carlo would create an incomplete and inconsistent assessment even for background uncertainties and was therefore not attempted.

One approach to addressing uncertainties is through varying the choices of the model, of the input parameters, or the surrounding conditions. Such choice variations have been referred to as scenarios in LCA (Pesonen et al., 2000). Like many cases in product development, system definition is a principal cause of uncertainty. Uncertainty is managed here by evaluation of multiple scenarios, an approach that is particularly relevant for systems not currently operating at a commercial scale. The principal uncertainties in such analysis depend on the definition of the scenarios rather than variability in measured input variables.

Following the terminology used by Pesonen et al. (2000), this study falls under the category of "cornerstone scenarios" for which the field of research is new, the purpose is to increase understanding of the subject, and the study consists of the design of a new product. Furthermore, the results of this study suggest more specific research, particularly for the case of the precipitation method as well as lower addition ratios for the case of green seaweed, which is also a characteristic of a cornerstone scenario.

6. Conclusion

This study shows the benefit of using LCA in ensuring that upstream supply chain impacts are considered and that impacts can be quantitatively assessed during product development, providing practical guidance to researchers and product developers in the field. Despite trying to find which protein ingredient would have lesser environmental impacts, we found that no herring co-product and helper combination provides a protein ingredient with lower environmental impacts in all categories investigated. The reason for this was the observed trade-off between climate change and land occupation impacts when comparing different helpers. This study is valuable in helping product developers move beyond an assessment that is limited to product yield, providing a more sophisticated assessment that has the function delivered in focus. The study indicated that within the range of parameter variations considered practical by food scientists developing this protein ingredient, the choice of processing version has a bigger influence on impacts than the helper addition ratio and the choice of helper. While a focus on the selection of helper inputs is warranted, we found that for the cases studied, the helper selection is not the most important factor in determining impacts other than land occupation.

Ethical Statement for Future Foods

Hereby, I Carla R. V. Coelho, confirm that the submitted manuscript does not represent a study involving humans or animals.

This material is the authors' own original work, has not been previously published elsewhere, and is not currently being considered for publication elsewhere. The paper reflects the authors' own research and analysis in a truthful and complete manner.

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.

CRediT authorship contribution statement

Carla R.V. Coelho: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing,

Visualization. **Gregory Peters:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Jingnan Zhang:** Conceptualization, Investigation, Writing – review & editing. **Bovie Hong:** Investigation, Writing – review & editing. **Mehdi Abdollahi:** Writing – review & editing, Supervision. **Ingrid Undeland:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Data Availability

Data will be made available on request.

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