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## Full length article

## Fish beyond fillets: Life cycle assessment of cross-processing herring and lingonberry co-products into a food product

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## ABSTRACT

The food industry generates side streams that can be used as sources of valuable compounds. We carried out a life cycle assessment of a protein ingredient obtained by pH-shift processing co-products of herring (*Clupea harengus*) and lingonberry (*Vaccinium vitis-idaea*) pomace. The assessment was based on a combination of primary and literature data to assess climate change, cumulative energy demand, land occupation, and depleted stock fraction impacts of marine resources. We analyzed the environmental profile of the fish protein ingredient on its own and as a consumable fish ball preparation. The potential impacts of the protein ingredient fish ball were compared with a benchmark fish ball and with salmon fillets. The results were generally favorable for the protein ingredient fish ball produced via cross-processing herring co-products and lingonberry pomace. This analysis supports the idea of further investment in cross-processing food sidestreams into a protein ingredient for food products.

## 1. Introduction

In recent years, animal protein consumption has increased (Ismail et al., 2020), with fish providing 17% of animal protein and 6.7% of all protein consumed by the human population (FAO, 2016). The seafood processing industries generate large amounts of side streams that can be a raw material for the production of marine proteins (protein isolate, fishmeal, silage, and hydrolysates), oils rich in long chain n-3 polyunsaturated fatty acids (LC n-3 PUFA), and preparation of high-value compounds such as vitamins, enzymes and minerals for various nutritional, pharmaceutical, and biomedical applications (Kim, 2014). When using fish processing side streams for the development of food ingredients, they must be handled in a food-grade manner, following basic operational and environmental conditions required to produce safe foods (Hayes, 2018). Hereafter, we will use the term “by-product” to refer to food processing industry outputs used in the animal feed industry, “co-product” will be used for outputs that are food grade and can be used for human consumption; “sidestream” is the collective term for both.

There is a developing interest in utilizing alternative cuts from the fish beyond those traditionally used for direct food consumption, i.e., the fillets (Petrova et al., 2018). This interest emerges from the valorization of food industry side streams being an integral part of a circular

economy. A study of the environmental impacts of processing anchovy filleting co-products into a fish paste (which can replace tuna or mussel pâté) highlighted the potential environmental benefits of such a valorization process (Laso et al., 2016). Several methods for extraction of fish proteins from co-products have been developed, for example, enzymatic hydrolysis (which breaks down the proteins into peptides), and pH-shift processing (which is protein solubilization at high or low pH followed by isoelectric precipitation) (Sanmartín et al., 2009). The protein recovered from fish co-products can be used in diverse applications, such as fish burgers, fish sausages, soup thickener, and mayonnaise (Björkner et al., 2019).

Fish contain PUFA that are highly susceptible to oxidation (Secchi and Parisi, 2016). Such lipid oxidation leads to unpalatable flavor and odor, color changes, reduced shelf life, losses of nutritional values, and possible production of harmful molecules (Secchi and Parisi, 2016). A variety of antioxidants can be used to inhibit or delay oxidation in food products and are classified into two categories, natural and synthetic, with natural antioxidants being increasingly preferred in muscle-based food products (Beya et al., 2021; Lorenzo et al., 2018; Raghavan and Richards, 2006; Ribeiro et al., 2019). Side streams of processed fruits may contain compounds with interesting techno-functional and nutritional value, such as pectin, proteins, antioxidants, carbohydrates, fibers, and vitamins (Campos et al., 2020). Many authors have researched

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the use of a variety of fruits and their co-products as natural antioxidants for meat products (Peiretti and Gai, 2015), but mainly in the form of extracts, which leaves a large extraction residual behind as a new sidestream.

Motivated by the potential utilization of proteins available in the heads and backbones of salmon (*Salmo solar*) and Atlantic herring (*Clupea harengus*), Abdollahi et al. (2020) investigated pH-shift-based cross-processing of salmon or herring co-products with lingonberry pomace, shrimp shells or seaweeds to produce protein isolates that are stable in respect to lipid oxidation during the processing. The authors concluded that an alkaline pH-shift while cross-processing fish side streams with lingonberry (*Vaccinium vitis-idaea*) pomace seems an approach for inhibiting lipid oxidation during processing.

Atlantic herring, a small pelagic fish found on both sides of the Atlantic Ocean, is one of the most abundant fish species in the world (EUMOFA, 2018) and is classified as a species of least concern under the IUCN classification (IUCN, 2009). In 2018, 1 million tonnes of Atlantic herring were captured by Norway, Denmark, Finland, Sweden, and Iceland, which together represent 57% of the global catches (FAO, 2020a). In Sweden, about 11,000 tonnes of herring were processed in 2018 (FAO, 2020b).

Lingonberries, commonly known as lingon, mountain cranberry, and cowberries are native to the circumpolar boreal region, including Scandinavia, Europe, Alaska, and northern Canada (Zhao, 2007). Lingonberry is primarily harvested from wild stands, and harvest statistics are difficult to obtain (Zhao, 2007). The amount of lingonberries available in the wild is dependent on the region and is subject to weather factors, which can result in stark variations in the amount of lingonberries available (SLU, 2016). In Sweden, the annual harvest is estimated at around 8000 tonnes a year, half of which is exported (Casimir et al., 2018).

Lingonberries are most commonly harvested by hand, using a rake similar to that used for lowbush blueberries (Zhao, 2007). In Sweden, the forest berry harvest is dependent on a workforce drawn from foreign countries. Each year between 2500 and 6000 Thai workers travel to Sweden to support the berry industry in occupations such as berry pickers, drivers, cooks, or camp leaders (Eerbeek, 2019). Pickers from European Union countries also work in the berry industry (Hedberg et al., 2019; Sjons, 2016). The picked berries are transported to cold stores, cleaned, packed, and delivered to customers (Sjons, 2016). If the berries are processed into juice, the lingonberry pomace is sold to the world market.

This study focuses on the environmental aspects of the co-product processing to extend the utilization of marine resources for human consumption. The production process for fish protein isolates by cross-processing herring heads and backbones with lingonberry pomace using an alkaline version of the pH-shift process will hereafter be referred to as “CROSS”, and the protein isolate will be referred to as protein ingredient. This paper has two main objectives: 1) the characterization of potential environmental impacts of the CROSS process using a life cycle assessment (LCA) perspective, and 2) the comparison of the environmental profile of the CROSS-derived protein ingredient as a consumable product with an existing commercial fish product. We present a quantitative assessment of the energy and material flows of the pH-shift process using LCA. We investigated whether such processing could provide a protein source that could contribute to a more environmentally sustainable food production system.

## 2. Method

### 2.1. Goal and scope

With the goal of identifying improvement potential for process designers, the CROSS-processing of herring co-products with lingonberry pomace was firstly assessed following a standalone LCA approach using a functional unit of “the provision of 1 kg of protein ingredient produced

from the co-processing of herring and lingonberry pomace generated in Sweden”. The protein ingredient is produced using pH-shift processing and is destined for human consumption after combination with other ingredients.

As assessing a final and consumable product is a meaningful LCA perspective we modeled the protein ingredient as part of a fish ball preparation. This was done using an existing salmon and cod fish ball currently available in the market in Sweden as a benchmark for formulation. More specifically, a fish ball containing the protein ingredient instead of salmon and cod mince, in addition to rapeseed oil, onions, garlic, seaweed, and rice was formulated to have similar calories and macronutrient profile as the benchmark, reflecting one possible route for consumption as a final product. An additional version of the fish ball formulation was modeled, replacing the rapeseed oil with oil derived from the CROSS-processing. The benchmark and the CROSS protein fish balls were compared on a mass basis using the functional unit of “the provision of 1 kg of fish balls, frozen, in Sweden”. Environmental impacts of food expressed per kilogram of food product can be converted to other measures considering the nutritional profile of the product. Here, as fish products can be considered as a source of protein in a meal, the results for the consumable product are also presented for the secondary functional unit of “100 g of protein, from frozen fish balls, in Sweden”.

The business-as-usual route for the herring side streams is processing into fish meal and fish oil and further into feed primarily for salmon aquaculture, therefore, the impacts of salmon fillets were compared to the fish balls. For the salmon fillet, the functional unit was “the provision of 1 kg of Norwegian aquaculture salmon fillet, frozen, in Sweden”. As such, making possible a comparison of 1 kg of a frozen fish product, i.e., fish balls or salmon fillets, in Sweden. A secondary functional unit of “100 g of protein, from Norwegian aquaculture frozen salmon fillet, in Sweden” allows a comparison of the salmon fillets and the fish balls on the protein basis. A diagram of the compared systems is shown in Fig. 1.

The intended audience for this work is primarily process designers, product developers, and business developers in the food industry, and sustainability researchers. We aim to inform their deliberations concerning an environmentally sustainable transformation of the food sector.

Multi-output processes of fish co-products used in the CROSS-processing, fish by-products used in the salmon feed, and pomace generation were handled by mass allocation. This choice follows the priorities expressed in ISO14044 (ISO, 2006), given that the mass flowrates of the outputs are mutually dependent and the subsequent utility of the flows depends on their mass. No allocation is applied to the CROSS-processing itself, meaning that all inventory flows are associated with the production of the protein ingredient.

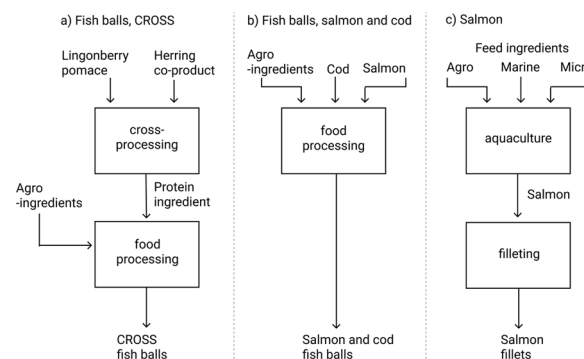


Fig. 1. Main material inputs to the systems compared a) fish balls made with the CROSS protein ingredient, b) fish balls made of salmon and cod (commercially available), and c) salmon fillets.

We selected impact categories for this study based on the overlap between environmental impacts of principal concern for seafood supply chains and the impact categories supported by adequate access to inventory data for these systems. Driven by anthropogenic greenhouse gasses emission, climate change (CC) poses several threats to the planet. We used the IPCC's 2013 global warming potentials based on a 100-year integration time and expressed in carbon dioxide equivalents ( $\text{CO}_{2\text{eq}}$ ). Energy consumption is a concern related to intragenerational equity for resource-intensive supply chains such as these and has explanatory power in relation to the investigation of contributions to climate change. We investigated energy consumption using cumulative, non-renewable, fossil energy demand (CED) in MJ. Land occupation is relevant because of the extensive use of farmed crops to produce fish feed and was accounted for in terms of land occupation (LO) in  $\text{m}^2 \cdot \text{year}$ . We used a recently published (dimensionless) potentially depleted stock fraction (DSF) indicator to quantify the impact on biotic resource depletion assessed at stock level. This indicator considers the mass of fish caught, the current marine biomass stocks, and their maximum intrinsic growth rates (Hélias et al., 2018). The impact of the depleted stock fraction ( $I_{\text{DSF}}$ ) is particularly relevant for comparing the impact of the fish balls and the salmon fillet as the primary motivation of the study is the conservation of marine resources.

### 3. Life cycle inventory

The CROSS process' raw materials are lingonberry pomace and herring heads and backbones. The study includes transportation of workers, harvesting of berries, cleaning and freezing of berries, and processing into juice. For the herring co-products, fishing activities and fish filleting were included. Energy and material input to the CROSS-processing were modeled by scaling from primary laboratory data to the industrial scale. The industrial-scale was designed for a full-scale equipment performance, considering the co-products' availability in Sweden. The packaging of the final products is not included in the analysis, and residual wastewater treatment is also not included for consistency of the compared systems. The LCA was modeled in OpenLCA 1.10.3. to represent the Swedish context using the Ecoinvent database version 3.7 with cut-off allocation (Wernet et al., 2016) and the Agribalyse 3.0.1 dataset (ADEME, 2020).

#### 3.1. Herring fishing and processing

The inventory for herring fishing was based on literature. The main fishing methods for herring are pair trawl and purse seine (Schmidt and Thrane, 2005). The median fuel consumption for Norwegian herring fishing vessels in 2017 was 0.086 liters of fuel/kg live weight (Ziegler et al., 2021). The data was converted to MJ, using a 37 MJ/liter conversion factor, the fuel consumption value was 3.2 MJ/kg caught herring, and the process "diesel burning in fishing vessel" from ecoinvent was used. Herring is usually landed without any form of processing onboard (Winther et al., 2020). Therefore, no losses had to be calculated at this life cycle stage. However, in commercial fishing operations, not all marine organisms that are caught are retained onboard, with these being called discards (Catchpole et al., 2005). More specifically, discards are unintended catches of non-target organisms (which are either not the targeted size or species) and which are thrown back at sea (whether they are dead or alive) (Pérez Roda et al., 2019). Discard rates depend on several factors, and in this study we based the discard rates on fishing gear type, based on the most common gear being purse seine in Norway (Tenningen et al., 2012; Ziegler et al., 2021). Purse seine discards represent 4.7% of the landed fish (Pérez Roda et al., 2019). In our model, we included discarded fish as an inventory input. As we could not retrieve information on a quantitative breakdown of the species

discarded in herring fisheries, and given that this study is the first attempt to include impacts of discards in LCA, we modeled discards as miscellaneous pelagic fishes. All other values were modeled based on anchovies captured by a steel purse seine and landed whole in Spain, in accordance with ecoinvent 3.7.

To model the herring filleting process in Sweden, we used primary data from one company representing about 70% of the market. More specifically, we obtained primary data for the breakdown of herring fillet amounts and co-products, and energy and water consumption. We obtained values of 0.221 kWh of electricity and 5.35 L of water per kg of whole herring. We modeled co-products of herring into CROSS using the heads plus backbones with the muscle tissue left on them after filleting. We obtained primary data for herring co-products breakdown of samples from August to September (Bita Forghani, unpublished results) and October (Wu et al., 2021). As the data for August to September measured the weight of fillets with skins, we used the value of 5.7% of the fish weight being skins in the October sample from Wu et al. (2021), and applied this data to all the samples to obtain the values of fillets without skins. As a result, the average data from these three months representing the herring fishing high season is 33% heads and backbones, 42.5% fillets without skin, and 24.5% other by-products. With this breakdown, we calculated that for 2.35 kg of landed herring, the yield is 1 kg of herring fillet, 0.77 kg of heads and backbones, and 0.58 kg of other side streams. The energy and material inputs were allocated to this multi-output process using mass allocation. The herring by-products are currently processed into fishmeal and fish oil in Denmark and are mainly destined for Norway as input to Salmon farming (personal communication, Martin Kuhlin from Sweden Pelagic, January 2021).

#### 3.2. Berry pickers transport, berry picking and processing

As the Swedish berry picking industry is almost entirely dependent on workforce which travels to Sweden for this exclusive purpose, the transportation of the lingonberry pickers to Sweden is considered part of the product system. These were included according to the distances reported in a case study for lingonberry jam in Sweden (Sjons, 2016). Workers from Thailand harvest 3.5 tonnes of berries per person, amounting to 40% of the harvest. Berry pickers from Bulgaria, Romania, Poland, Ukraine, and Sweden harvest 2.5 tonnes of berries per person, collecting 60% of the total harvest (Sjons, 2016). In addition to the 8070 km of the Thai workers' long-haul air travel, a 340 km distance by bus was included to represent the distance between the airport and the berry picking region (Sjons, 2016). Distances traveled by other berry pickers were also drawn from the same report, being 3367 km from Sofia, 3132 km from Bucharest, 2028 km from Warsaw, 2793 km from Kyiv, and 150 km within Sweden (Sjons, 2016). All distances values presented here represent one-way travel to Sundsvall in Sweden. Following the same report, the type of passenger car used in our model runs on petrol (EURO 4 emissions standard), with four passengers per vehicle for workers traveling to Sweden by car, and two passengers per vehicle for Swedish workers.

Berry picking, cleaning, and freezing processes were based on the values reported for lingonberries in Sweden (Sjons, 2016), and the values we report refer to handling 1 tonne of harvested berries. Lingonberries are manually harvested and put into HDPE crates, being 2.5 kg of HDPE packaging per tonne of harvested berries. Electricity consumption includes 637.5 kWh for freezing, 850 kWh for frozen storage for four months, and 85 kWh for cleaning of berries. 170 kg of water is used per tonne of harvested berries. Each tonne of harvested lingonberry yields 0.85 tonnes of cleaned and frozen lingonberries. Primary packaging is made of 6.0 kg kraft paper and 0.2 kg of LDPE per tonne harvested. Secondary packaging consists of 6.8 kg cardboard octabins, and 0.62 kg LDPE covering per tonne of harvested berry.

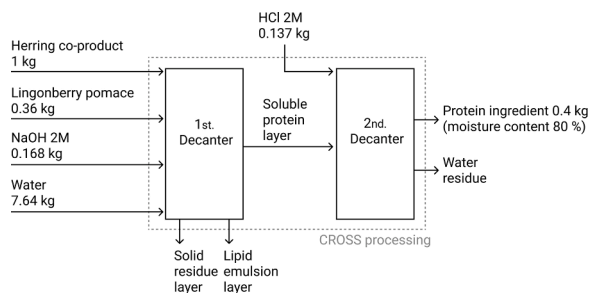


Transport distances for the lingonberries and vehicles-types were modeled according to the report on lingonberries processed into jam in Sweden (Sjoms, 2016) being: 400 tkm in passenger-type vans during harvest, and a total of 1112 tkm in chilled transport. Berries are crushed, heated, and pressed for the extraction of raw juice. For processing into juice, we used data from the literature for blackcurrant juice (May and Guenther, 2020), which refers to the processes of crushing, mashing at 50 °C for 2 to 3 h, pressing, and separation. Energy consumption was 0.13 kWh/kg of berries pressed and modeled here as Swedish electricity. Steel for the juice processing machinery, consisting of box dumper, crushing machine, stainless steel tank, stirrer, belt press and centrifuge, were added and divided by the reported value of berries processed by May and Guenther (2020), calculated to be  $9.12 \times 10^{-5}$  kg steel/kg of berries pressed. After juice pressing, lingonberry pomace represents approximately 15.3% of the fresh berry mass (Kitrytė et al., 2020), mass allocation was applied to the inventory flows associated with the juice and pomace.

### 3.3. CROSS-processing

The inventory modeling of the cross-processing of the herring co-products with lingonberry pomace was based on the experimental results. The system is modeled after Zhang et al. (2022) in which industrially processed lingonberry pomace was used in the cross-processing following the same method as Abdollahi et al. (2020). Herring heads and backbones were processed with lingonberry pomace at 30% (dw/dw) addition. For 1 kg of herring heads and backbones, 0.36 kg of industrial lingonberry pomace and water input of 7.64 kg would be required (Zhang, unpublished results). The process also uses 0.168 g of 2 molar sodium hydroxide. We calculated the active substances to be  $1.24 \times 10^{-2}$  kg of NaOH. The mixture is subjected to homogenization, stirring, and two decanting processes. The first decanter is three-phase and outputs a solid residue, lipid emulsion, and a soluble protein layer. As the main purpose of the process is to produce a protein ingredient, we have not allocated inventory flows to the solids and lipid emulsion layer. The soluble protein layer is then stirred with an addition of 0.137 kg of 2 molar hydrochloric acid, which is calculated as  $8.3 \times 10^{-3}$  kg of HCl. A second decanting process takes place, separating the water from the protein using a two-phase decanter. At laboratory scale, the protein ingredient must then undergo additional centrifugation in order to reduce the moisture content to 80% to allow it to be usable in commercial applications resulting in a yield of 0.4 kg of protein ingredient. The material flows directly associated with the CROSS process are presented in Fig. 2.

The CROSS-processing was assumed to take place in Sweden. It is reasonable to expect that such processing would occur near the fish



**Fig. 2.** Material flows of the CROSS process for a reference flow of 1 kg of the protein product at 80% moisture content. In this figure, the 2<sup>nd</sup> decanting and the additional centrifugation processes are presented as part of the 2<sup>nd</sup> decanter.

processing facility; therefore, a transport distance of 40 km was taken into account to represent the travel from the filleting factory to the CROSS processing site. The berry pomace transport from the juice processing facility to the CROSS processing facility was included as a 300 km truck trip. The process at laboratory scale is done on ice (Abdollahi et al., 2020; Zhang et al., 2022). At an industrial scale, the process would run at cool room temperature.

### 3.4. Process dimensioning for industrial scale

To model the CROSS-processing, it was necessary to estimate the scale of the operation at industrial scale. The first step is estimating how much co-products it is available of both co-products. The FAO estimated that 11,000 tonnes of herring were processed in Sweden in 2018 (FAO, 2020b). Our primary industry data indicates that heads and backbones represent about 33% of the weight of the landed herring, meaning that around 3600 tonnes of herring co-products could be provided for the cross-processing. For lingonberries, the annual harvest estimate is 8000 tonnes per year, half of which is exported, and the remainder is mainly processed into juice concentrate and jam (Casimir et al., 2018). The amount processed specifically into juice was not provided in that source. We contacted a lingonberry juice producer in Sweden who opted to remain anonymous, and based on the expert information provided, we estimated that about 140 tonnes of lingonberry pomace are generated in Sweden after a normal year's harvest. We also judged it reasonable to consider that not all pomace would be available for cross-processing and used a value of 100 tonnes of pomace. As lingonberry pomace is the limiting ingredient, a scaled-up process using the 100:36 ratio of herring to lingonberry would handle 278 tonnes of herring co-products and 100 tonnes of lingonberry pomace.

### 3.5. Energy consumption for storage and facility refrigeration

Both lingonberries and herring are seasonal products and we have considered that both products can be stored for a year if frozen. Herring high season is reported to be between August and November (Theiliander, 2017). We then calculated that the 278 tonnes of herring co-products will arrive at storage in four months of the year, and being processed 11 months of the year, an output rate of 9% is observed every month between August and June. The maximum storage is expected to happen in November and represents 64% of the total herring volume processed by CROSS, meaning that 178 tonnes of herring heads and backbones need storage. For lingonberries, the high season is mid-August to mid-October (Forststyrelsen, 2021), meaning that the maximum amount of pomace to be stored is 64% of the total annual flow, i.e., the maximum storage would be 64 tonnes of berry pomace in December. The density of the herring co-products was assumed to be 0.93 kg/L (Machine and Process Design, 2021). For lingonberry pomace, the value of 0.9 kg/L was used based on lowbush blueberries' pomace tapped density (Ross et al., 2020). Herring and lingonberry pomace were modeled to be stored in 210 liters HDPE barrels weighing 9 kg each. We calculated the maximum number of drums required using the volume and maximum amount of the raw materials. The volume of storage was calculated taking into account the pallet area, the number of drums per pallet, two-level shelving for the pallets, and the assumption that the floor area necessary for forklift maneuvering is about equal to the shelf area. With a 4 m high ceiling, we estimated that 3640 m<sup>3</sup> cold store room volume is needed, plus a 4000 m<sup>3</sup> factory volume for processing at a cool temperature. Values necessary for the calculation of the storage facility are presented in Table S1 in the Supplementary Material (SM).

Regarding the performance of cold stores, Evans et al. (2015) observed a trend across climatic zones regarding energy consumption for chilled stores, with higher energy consumption in warmer climates,

but saw no significant trend in energy consumption for (colder) frozen stores. Therefore, in our study, the frozen storage energy consumption was modeled as the mean value of the global dataset with the upper 20% removed, being 66 kWh/m<sup>3</sup>/y following Evans et al. (2015). For the chilled processing, a value of 35 kWh/m<sup>3</sup>/y was approximated from the mean specific energy consumption for cold climates (Evans et al., 2015). We calculated that 1.22 kWh/kg of CROSS protein product is required for the chilling effort of the facility.

### 3.6. CROSS-processing energy consumption

In the CROSS-processing, the industrially sourced lingonberry pomace and the fish co-products are minced in a grinder with a 4.5 mm hole (Zhang et al., 2022). Grinding energy consumption depends on the size of the particle and ranges from 8 to 16 kWh/tonne (Piccinno et al., 2016), and here it was modeled as the worst-case scenario. Therefore, we used values of  $1.6 \times 10^{-2}$  kWh/kg of herring co-products. The co-products are mixed with water and homogenized. Energy consumption for homogenization using a rotor-stator type homogenizer ( $E_{hom}$ ) can be calculated as stirring energy ( $E_{stir}$ ) as a homogenizer can be regarded as stirring at very high shear rates (Piccinno et al., 2016). Energy consumption can be estimated in joules (J) using data in SI-units (Zlokarnik, 2000) in the following equation:

$$E_{hom} = E_{stir} = \frac{N_p \times \rho_{mix} \times N^3 \times d^5 \times t}{\eta_{stir}}$$

where  $N_p$  is the power number associated with an impeller type,  $\rho_{mix}$  is the density of the reaction mixture,  $N$  is the rotational speed of agitator,  $d$  is impeller diameter,  $t$  is reaction time, and  $\eta_{stir}$  is the efficiency of the agitator. As the mixture is composed of 85% water, we used water density at 4 °C, 1000 kg/m<sup>3</sup> as a proxy for the density of the reaction mixture ( $\rho_{mix}$ ). Homogenization of herring co-products is complete after 90 s at laboratory scale (Zhang et al., 2022). To calculate the total volume to be processed, we assumed a normal Swedish working year, minus 3 weeks maintenance downtime, i.e., 45 weeks in a year, 5 days a week, and 8 h a day; we calculated a processing flow of 1.4 tonnes/hour. The homogenizing energy requirement was calculated for a 500 L vessel, a scale that provides time for filling and emptying operations without investing in excessive capacity. For this scale, Piccinno et al. (2016) suggests an impeller diameter of ( $d$ ) 0.111 (m), power number of the rotor ( $N_p$ ) 2.39, rotational speed of the rotor ( $N$ ) 48.333 (1/s), and efficiency of the agitator ( $\eta_{stir}$ ) 0.9. The  $E_{hom}$  was calculated to be 0.45 MJ/batch, or  $2.29 \times 10^{-3}$  kWh/kg of herring co-products.

We modeled the pH-shifting reaction stirring ( $t$ ) as 10 min, which was adequate at laboratory scale. Stirring energy was also calculated based on the data suggested by Piccinno et al. (2016) for a 1000 L capacity process, with impeller diameter of ( $d$ ) 0.373 (m), power number of axial flow impeller ( $N_p$ ) 0.79, rotational speed of agitator ( $N$ ) 1.42 (1/s), and efficiency of agitator ( $\eta_{stir}$ ) 0.9. The calculated  $E_{stir}$  was 10.8 kJ/batch. The stirring energy requirement is therefore  $2.80 \times 10^{-5}$  kWh/kg of herring co-products.

After the first step of the pH-shift process, oil, solid, and soluble protein separation is carried out through centrifugation and sieving

(Abdollahi et al., 2020; Zhang et al., 2022). For the estimation of the energy consumption at industrial scale, this three-phase separation is expected to be done using a first decanter, in which the soluble protein is separated from the oil and the solids, and a second decanter is then used to reduce the water content of the soluble protein. Power curves for the decanter equipment were obtained, and the bowl speed was selected. The first decanter inflow would require a 6.5 kW decanter, according to the power curves of the appropriate equipment. As the process is designed to operate 45 weeks in a year, 5 days a week, and 8 h a day, and processes 278 tonnes of herring co-products in a year, the electricity consumption of the first decanter was calculated to be  $2.25 \times 10^{-2}$  kWh/kg of herring co-product. For the second decanter, considering its inflow of soluble protein and its specific technical requirements, a decanter of 9.2 kW input power would be needed, meaning an energy consumption of  $3.18 \times 10^{-2}$  kWh/kg of herring co-product for the second decanting step.

### 3.7. Benchmark product and salmon fillet

As a benchmark for comparison, a consumer product was modeled to represent a commercially available fish ball made of salmon, cod, and other ingredients. Salmon and cod were modeled following the report on Norwegian seafood products from Winther et al. (2020). The modeling includes salmon feed and farming, cod fishing, processing, and transport.

Norwegian salmon feed is composed of marine ingredients at 27% on a mass basis, agricultural ingredients amount to 70% of the feed and include meal and oils, while micro-ingredients represent 3% of the feed and contain amino acids, phosphate, pigment, and vitamins (Winther et al., 2020).

The marine feed is subdivided by type (fishmeal and oil) and source (reduction and by-products), consisting of 16 different fish species (Winther et al., 2020). Pelagic fish constitute 24% of the feed, white fish by-products 1%, and krill 0.91% (Winther et al., 2020). To model the discards associated with the marine ingredients, discard rates and species composition for each of the 16 species used in the salmon feed would be required. Since such information is not readily available and compiling this data was considered out of the scope of this study, a simplified approach was taken. For pelagic fishes, the discards were modeled as the same as herring for simplicity. For white fishes, a discard rate of 30.9% for otter bottom trawling was used, following Pérez Roda et al. (2019), and the species modeled as miscellaneous demersal species. Krill fisheries discards were modeled based on discard rates for the FAO Antarctic fishing zone of 7.5%, from Pérez Roda et al. (2019), modeled as krill (*Euphausia superba*).

Fish meal and fish oil processing data was used from ecoinvent changing the electricity mix to represent the appropriate location for the respective feed ingredient. Description of the fishmeal and oil background datasets and production countries, as well as transport distances are found in the supplementary material (SM). Inventory data for amino acids, vitamins, and monocalcium phosphate were obtained from Agribalyse. Astaxanthin (pigment) was modeled according to the values provided by Winther et al. (2020). Specific datasets used are described in the SM. Input values of diesel, electricity, heat, and LPG for feed

**Table 1**

Comparison of nutritional profiles for the commercially available salmon and cod ball, for its modeled formulation, and for the fish ball made with the CROSS protein ingredient.

Product	Wet mass (g)	Calories (kcal)	Protein (g)	Fat (g)	Carbohydrate (g)
Salmon & cod balls, commercially available, precooked	100.00	160.00	17.00	7.00	6.90
Modeled salmon & cod balls	109.00	164.61	18.12	6.98	7.20
CROSS protein ingredient fish balls	109.00	161.16	14.60	7.70	9.30

production as well as feed ratio of 1.32 kg of feed per kg salmon slaughtered and sold were obtained from Winther et al. (2020).

For salmon aquaculture, electricity for sludge drying, electricity for juvenile production, electricity and lighting, and diesel for well boats, are included with values extracted from Winther et al. (2020), and are also reproduced in the SM. A floating collar cage was also included in the model. The cage size was calculated based on the descriptions of a traditional open net-pen production system in Norway: 157 m diameter, 40 m depth, with 578,000 m<sup>3</sup> rearing volume, and 25 kg of fish/m<sup>3</sup> (Liu et al., 2016). In the inventory, the functional unit of the collar cages is expressed as per meter of diameter, which was calculated to be 1.07 x 10<sup>-5</sup> m per kg of fish.

To formulate the salmon and cod fish balls, we considered a weight loss of 9 g of water per 100 g of final product in the industrial cooking process, following the “fish croquette” processing in the Agribalyse database. Prioritizing a similar macronutrient profile to the one in the salmon and cod fish ball nutritional information provided in the packaging of the commercially available product, we modeled a salmon and cod fish ball preparation to contain: 64 g of salmon mince, 29 g of cod mince, 8 g of rice, 4 g of onion, 2 g of garlic, 1.5 g of rapeseed oil, and 0.5 g of seaweed. Macronutrient profiles of the ingredients and further details on how the salmon and fish ball was formulated are shown in the SM. Cooking was based on deep-frying cooking process from Agribalyse, input datasets are presented in the SM.

Freezing of the fish balls was modeled as blast freezing. Blast freezing quickly changes the temperature, avoids the growth of bacteria and is applicable to pre-cooked meals (Dempsey and Bansal, 2012). Blast freezing energy consumption has been reported to be between 83 and 2744 kWh/tonne of food (Swain, 2006). As no specific details of the distribution of the data was provided, we used the mid-point value to account for the freezing of the fish balls after cooking, resulting in 1.4 kWh/ kg of fish ball.

### 3.8. CROSS protein ingredient-based fish balls

A fish ball was formulated as consisting of the CROSS protein ingredient, rice, onion, garlic, seaweed, and oil. The product was formulated to have similar macronutrients and calories to the commercial salmon and cod fish ball, which is commercially available. We modeled the CROSS fish ball with 86 g CROSS protein ingredient, 3 g of garlic, and 5 g of all other ingredients, for details of modeling and macronutrient profile see the SM. The final macronutrients and calories profile of commercially available fish balls, the modeled salmon and cod fish balls, and the CROSS protein product fish balls are presented in Table 1.

For the fish ball produced with the CROSS protein ingredient two versions will be investigated, one using rapeseed oil (as in the benchmark fish ball), and one replacing the oil with oil generated from the CROSS process itself. Industrial cooking and freezing of the fish balls formulated with the CROSS protein ingredient are the same as for the benchmark fish balls.

### 3.9. CROSS oil

We modeled a fish ball formulated with oil derived from the CROSS process instead of rapeseed oil. The CROSS process first decanting generates a lipid emulsion layer containing water which needs to be removed for utilization of the oil in a food preparation. Based on experimental results and mass balance, we estimated that 30 g of lipid emulsion layer is generated per 100 g of processed herring co-products. This value was scaled to the annual volume of herring co-products to be processed, being 83 tonnes of lipid emulsion layer would be generated in a year. The lipid emulsion was modeled to be processed in a disk stack centrifuge with a capacity of 4 m<sup>3</sup>/h, and 15 kW of motor power (ZK Separation, 2022). An oil yield of 4.6 g of oil can be obtained from cross-processing 100 g of fish co-product (Abdollahi and Undeland,

2020), resulting in a calculated energy consumption of  $2.44 \times 10^{-2}$  kWh/kg of oil extracted.

## 4. Results

### 4.1. Inputs to CROSS process

The input flows for the cross-processing of herring co-products and lingonberry pomace producing 1 kg of protein ingredient with approximately 80% of moisture content are presented in Table 2.

### 4.2. Life cycle inventory results, CROSS process

The outcome of the life cycle inventory analysis cataloging the flows crossing the system boundary provides the basis for the life cycle impact assessment. The flows that are relevant to the assessed impact categories and contribute more than 0.01% of the impact assessment results for each respective category are presented in Table 3.

### 4.3. Life cycle impact assessment results

#### 4.3.1. Contribution analysis, protein ingredient

The modeled CROSS protein ingredient results in contributions to CC of 2.4 kg CO<sub>2eq</sub>, CED of 33.25 MJ, LO 0.64 m<sup>2</sup>•year, and I<sub>DSF</sub> of  $3.8 \times 10^{-10}$  for 1 kg of CROSS protein ingredient. The contribution analysis for these categories and the fish species mass ratio are presented in Fig. 3. The impact assessment category CC and the inventory analysis CED contributions presented a very similar profile, herring co-products contributing to around 45% of these potential impacts, and lingonberry pomace accounting for 37%. For land occupation, electricity for the CROSS-processing, primarily for storage and chilling, and berry juice processing amounted to 53% of the contribution. An analysis of the Swedish electricity mix contributions to land occupation revealed that 54% is attributed to heat and co-power generation from wood chips due to forest occupation, despite being responsible for a small share of the energy mix, followed by 22% from hydropower and 15% from the Norwegian electricity mix. In terms of fish species, miscellaneous pelagic fishes, with a discard rate of 4.7% of the total catch, accounted for 60% of the I<sub>DSF</sub> impact.

#### 4.3.2. Contribution analysis, CROSS fish ball

The modeled fish ball containing the CROSS protein ingredient has a contribution to CC of 2.8 kg CO<sub>2eq</sub>, CED of 36 MJ, LO of 1.6 m<sup>2</sup>•year, and I<sub>DSF</sub> of  $3.3 \times 10^{-10}$  for 1 kg of CROSS protein ingredient-based fish ball.

**Table 2**

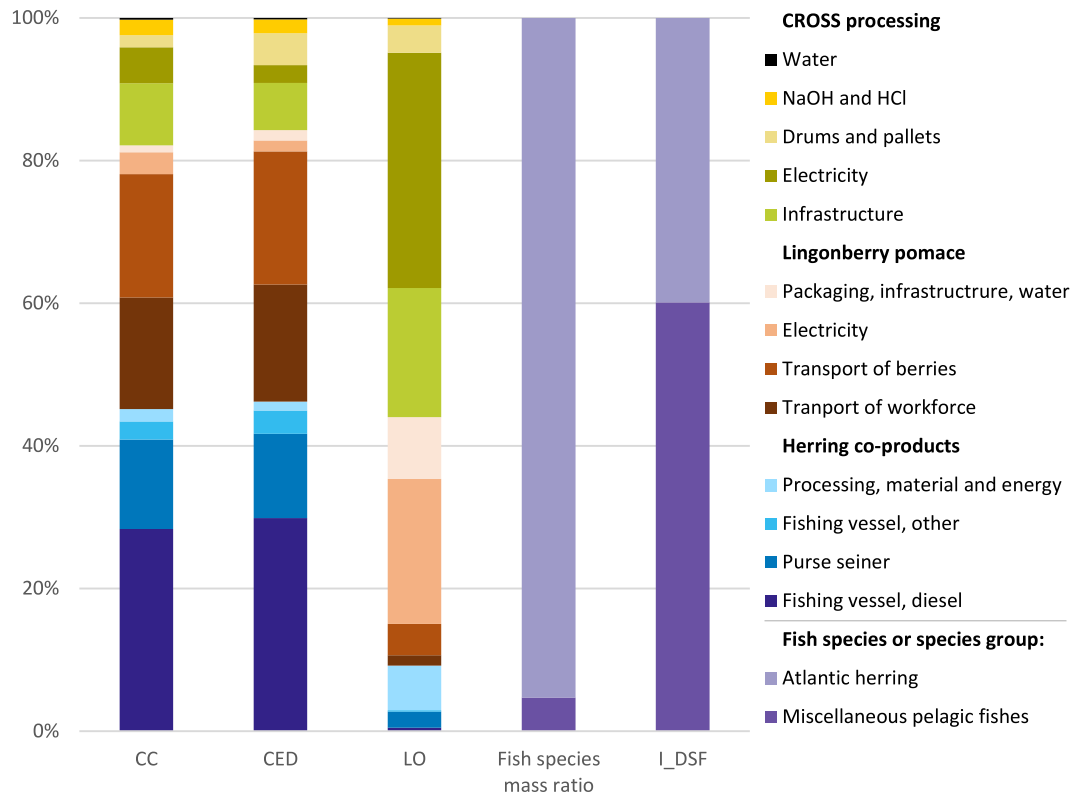
Inputs to processing of herring heads and backbones (fish) with lingonberry pomace (helper), producing 1 kg of protein ingredient.

Material and energy inputs		Quantity
Material inputs	fish (kg)	2.5
	helper (kg)	0.9
	water (kg)	19.1
	NaOH (kg)	0.4
	HCl (kg)	0.3
Infrastructure and storage material	area (m <sup>2</sup> )	$5.23 \times 10^{-4}$
	EU-flat pallet (unit)	$2.79 \times 10^{-4}$
	equipment, steel (kg)	$5.12 \times 10^{-3}$
Processing electricity	electricity, grinding, fish (kWh)	$4.00 \times 10^{-2}$
	electricity, grinding, helper (kWh)	$1.44 \times 10^{-2}$
	plastic drums for storage (kg)	$2.01 \times 10^{-2}$
	temperature control (kWh)	$3.03 \times 10^0$
	1 <sup>st</sup> homogenization (kWh)	$5.68 \times 10^{-3}$
	1 <sup>st</sup> stirring (kWh)	$6.88 \times 10^{-5}$
	1 <sup>st</sup> decanter (kWh)	$5.62 \times 10^{-2}$
	2 <sup>nd</sup> stirring (kWh)	$5.22 \times 10^{-5}$
	2 <sup>nd</sup> decanter (kWh)	$7.95 \times 10^{-2}$
	Outputs	
	protein ingredient (kg)	1.00

**Table 3**

Relevant life cycle inventory results for the CROSS process, producing 1 kg of protein ingredient with approximately 80% moisture content.

	Flow	Inventory result	Unit
Resources	Oil, crude	0.53	kg
	Gas, natural	0.13	m <sup>3</sup>
	Coal, hard, unspecified	0.18	kg
	Coal, brown	0.05	kg
	Peat	0.01	kg
	Occup., forest, intensive, normal	0.38	m <sup>2</sup> • a
	Volume occupied, reservoir	0.14	m <sup>3</sup> • a
	Occup., tropical rain forest	0.04	m <sup>2</sup> • a
	Occup., traffic area, road network	0.02	m <sup>2</sup> • a
	Occup., water bodies, artificial	0.02	m <sup>2</sup> • a
	Occup., traffic area, road embankment	0.01	m <sup>2</sup> • a
	Occup., water courses, artificial	0.01	m <sup>2</sup> • a
	Occup., dump site	0.01	m <sup>2</sup> • a
	Occup., mineral extraction site	$3.89 \times 10^{-3}$	m <sup>2</sup> • a
	Occup., industrial area, built up	$3.39 \times 10^{-3}$	m <sup>2</sup> • a
	Occup., arable, non-irrigated, monotone-intensive	$2.33 \times 10^{-3}$	m <sup>2</sup> • a
	Occup., arable land	$2.30 \times 10^{-3}$	m <sup>2</sup> • a
	Miscellaneous pelagic fishes	0.12	kg
	Atlantic herring, <i>Clupea harengus</i>	2.50	kg
Emissions to air	Carbon dioxide, fossil	2.22	kg
	Methane, fossil	$3.51 \times 10^{-3}$	kg
	Carbon dioxide, from land transformation	0.02	kg
	Sulfur hexafluoride	$7.27 \times 10^{-7}$	kg
	Dinitrogen monoxide	$9.51 \times 10^{-5}$	kg
	Methane, biogenic	$2.80 \times 10^{-4}$	kg



**Fig. 3.** Contribution analysis of material and energy flows for the CROSS-processing of herring heads and backbones and lingonberry pomace into a protein ingredient. CC is climate change, CED is cumulative energy demand, LO is land occupation, and I\_DSf is the impact of depleted stocks fraction. Here fish species group “Miscellaneous pelagic fishes” represents fish discards from herring fishing using purse seine methods.



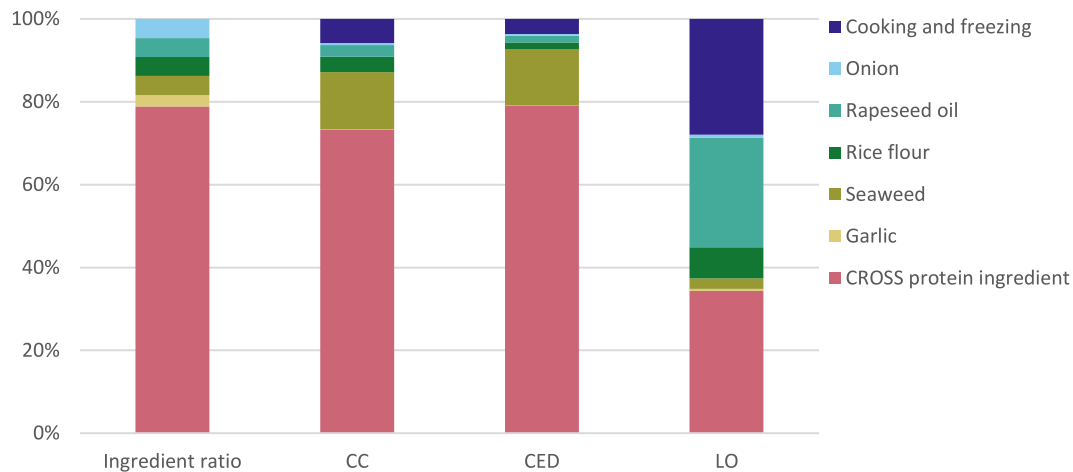


Fig. 4. Contribution analysis of ingredients and cooking process for the CROSS protein ingredient based fish balls at the processing facility.

The contribution analysis for the fish ball ingredients and cooking are presented in Fig. 4 alongside the fish ball ingredient composition. In the modeled fish ball, the CROSS protein ingredient accounted for 73% and 79% of the CC and CED categories, the seaweed production was the second-highest contributor to these two categories due to energy required by the drying process. Cooking accounted for 3.9% and 2.6% of the CC and CED, respectively. Freezing contribution to CC and CED was 1.9% and 1.0%, respectively. For land occupation, rapeseed oil contributed 26% of the total LO, and cooking represented 22% of the total, being almost in its entirety due to vegetable oil for cooking.

In investigating the potential impacts of the fish ball made with the CROSS protein ingredient, we considered an alternative preparation replacing the vegetable oil in the formulation with the oil generated from the CROSS process itself. This replacement resulted in a CC, CED, and  $I_{DSF}$  which were very similar to the rapeseed oil version, and a LO value of  $1.18 \text{ m}^2 \cdot \text{year}$ , for 1 kg for the CROSS protein ingredient fish balls prepared with CROSS process derived oil instead of rapeseed oil.

#### 4.3.3. Contribution analysis, salmon and cod fish ball

The modeled fish ball made of cod and salmon resulted in a contribution to CC of  $4 \text{ kg CO}_{2eq}$ , CED of 39 MJ, LO of  $3.4 \text{ m}^2 \cdot \text{year}$ , and  $I_{DSF}$  of  $1.28 \times 10^{-9}$  for 1 kg of fish ball. For this product formulation, salmon was the most contributing ingredient in all impact categories (Fig. 5). For the CC category, 40% of the fish ball impact was derived from salmon marine feed, 28% from agro-ingredients, and 6% from micro-

ingredients. Fishmeal and fish oil from reduction fisheries dominated the impact of the fish ball in terms of use of marine biotic resources being 77% of the total, followed by fish oil from by-products (15%), and fish meal from by-products (3%), and cod representing 4% of the total  $I_{DSF}$ .

#### 4.3.4. Product systems comparison

A comparison of the four product systems investigated, namely a CROSS protein ingredient-based fish ball using rapeseed oil in the preparation, a fish ball using CROSS protein ingredient and the CROSS oil layer in the formulation, a fish ball made of salmon and cod, and salmon fillet is presented in Fig. 6 on a mass basis and a protein basis, with the absolute values of the different product systems compiled in a comparative table in the SM. The salmon fillet's climate change impact was  $5 \text{ kg CO}_{2eq}$ , CED of 52 MJ, LO of  $4 \text{ m}^2 \cdot \text{year}$ , and  $I_{DSF}$  of  $1.86 \times 10^{-9}$  for 1 kg of fillet. A potential reduction of the impacts in all categories investigated is observed for the fish ball made with the CROSS protein ingredient compared with either the fish ball made of salmon and cod or the salmon fillet on a mass basis. The salmon fillet's climate change impact was  $2.7 \text{ kg CO}_{2eq}$ , CED of 28 MJ, LO of  $2.2 \text{ m}^2 \cdot \text{year}$ , and  $I_{DSF}$  of  $9.9 \times 10^{-10}$  per 100 g of protein. Compared to fish balls made of salmon and cod on a protein basis, the salmon and cod fish ball performed better than the CROSS fish balls in terms of CED category due to the lower protein content of the CROSS fish ball formulation. However, for the potentially depleted stock fraction category, the CROSS fish balls deliver

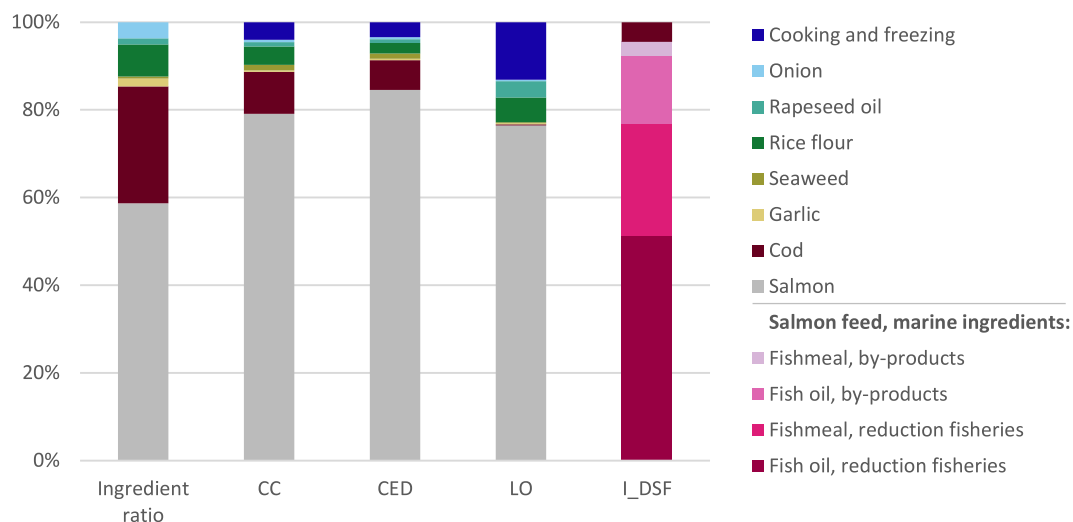
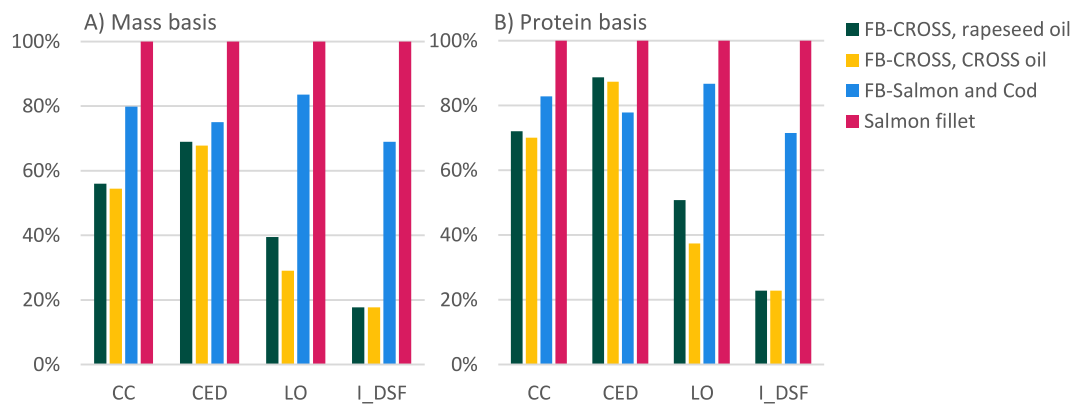


Fig. 5. Contribution analysis of ingredients and cooking process for the salmon and cod fish balls at processing facility.



**Fig. 6.** Comparison of three fish ball (FB) food options investigated in this paper, relative to the impacts of salmon fillets. FB-CROSS, rapeseed oil, represents a fish ball preparation with the CROSS protein ingredient and rapeseed oil, FB-CROSS, CROSS oil, represents a fish ball which uses CROSS process derived oil instead of rapeseed oil, FB-Salmon and Cod, represents the modeled benchmark fish ball, while Salmon fillet represents salmon fillet. A) Impacts were calculated for 1 kg of each product and B) impacts calculated for 100 g of protein in each product.

100 g of protein with a potential reduction of almost 80% when compared to the salmon fillet.

## 5. Discussion

The development of the CROSS protein ingredient is justified by the interest in the valorization of marine resources together with the addition of antioxidant properties of lingonberries (Abdollahi et al., 2020). Our study showed through the LCA method that the investigated fish balls designed with the CROSS protein ingredient presented a lower environmental impact when compared to any other alternative investigated on a mass basis. Fish balls for human consumption made with the CROSS protein ingredient have potentially less environmental impacts than salmon fillet in all categories when assessed on a protein delivery basis.

### 5.1. Seafood consumption

The Swedish Dietary Guidelines recommend increasing fish and seafood consumption in all forms and without limitation to any particular fish or type of preparation (Livsmedelsverket, 2015). A Swedish survey showed that regionality and sustainable production methods are among the most important factors for consumer perceptions of food of high quality, with the perception of quality having a strong positive correlation to buying decisions (Bosona and Gebresenbet, 2018). Additionally, there is a market trend in Sweden where traditional local food is appreciated next to the willingness and desire for new experiences and flavors (Antonissen, 2020). The joint presentation of herring and lingonberries is typical in Swedish culinary traditions, so even though they are not normally integrated within a fish ball it is reasonable to expect that this combination also may favor the CROSS fish ball investigated here. Further investigations on sensorial analysis are ongoing, and analyses of consumer acceptance, and market analysis among others, would also have to be carried out to verify the suitability of the CROSS protein ingredient to be used as a basis for a fish ball preparation.

### 5.2. Improvement opportunity

In this study, all environmental burdens of the cross-processing have been allocated to the protein ingredient, but the lipid emulsion and solids layer generated during the three-phase decanting process are not necessarily waste. Solids residues and lipid emulsion layer from the centrifugation of pH-shift can be further processed for the extraction of collagen and oil, respectively (Abdollahi et al., 2018; Abdollahi and Undeland, 2020). The main objective of the CROSS-processing is to extract the protein from the fish co-products, meaning that during the

CROSS-processing, oil is removed. Therefore, the LC n-3 PUFA content of a CROSS fish ball may be low compared to other marine protein sources. One alternative we investigated was the use of the CROSS processes-derived oil in the fish ball, potentially providing a superior product in terms of nutrition and environmental performance. The replacement of vegetable oil in the CROSS protein fish ball formulation reduced the land requirement per kg of fish ball. Other potential alternative uses for these side streams, such as the use of the oil in applications that are not in combination with the protein ingredient, would have to be considered as a multi-output process, potentially carrying some of the environmental burdens, likely reducing the impact of the protein ingredient via allocation procedures.

We have modeled the CROSS process to handle as much marine co-products as possible considering the limited supply of lingonberries following the 30% (dw/dw) addition ratio used in laboratory scale following Abdollahi et al. (2020). Reducing the quantities of the lingonberries needed in the process can allow more herring co-products to be processed. From the results of the CROSS process, it can also be inferred that reducing the berry to herring ratio would bring fisheries operations even more into focus for additional attempts to reduce the potential impact of the food product. Previous studies have identified that reducing fuel consumption can have the potential to effectively reduce the environmental impacts of seafood (Ziegler et al., 2016). Therefore, products utilizing the CROSS protein ingredient, as any food from marine fisheries resources, would benefit from more efficient fishing systems.

The study at hand found that the protein ingredient's major impact contributors to climate change and cumulative energy demand are the herring co-products and lingonberry pomace. However, the use of other helpers is also possible. Indeed, as shown in the work of Abdollahi et al. (2020) and Zhang et al. (2022), herring co-products can also be cross-processed with different helpers such as seaweed or apple pomace. As investigations in terms of process improvements are ongoing, we encourage further LCAs to be carried out to identify if the use of other helpers can result in a protein ingredient with potentially lower environmental impact.

### 5.3. Nutritional aspects and functional unit

We initially presented the LCA of a protein ingredient to identify potential hotspots and improvement opportunities to the process. When applying life cycle thinking it is paramount to also reflect on the product's function and how it will be used. For the protein ingredient, several applications may be possible, here we selected an application that already exists, a fish ball. We used the macronutrients and calorie profile to model a consumable product which would allow an LCA comparison

to be carried out for similar products. The nutritional profile was estimated theoretically and should be interpreted considering potential limitations introduced by this simplified modeling. In addition to the final product properties, which may require alteration of ingredients, the macronutrient profiles and calories are modeled based on the ingredients used in the proposed preparation and do not include fat absorption during frying.

The fish balls and the salmon fillet can be qualitatively described as providing the protein share of a meal. For the functional unit we calculated the impacts on a mass basis, but we also used 100 g of protein as a basis for comparison. Presenting results in terms of protein seems suitable for a product that is intended to be a protein source in a consumable portion. Indeed for protein-rich products such as meat, fish, and nuts, environmental impacts have been published on a protein basis (Poore and Nemecek, 2018). The message provided using these alternative functional units regarding the relative environmental performance of these particular alternatives is broadly similar. We argue that the comparisons of the fish ball and salmon both on mass and on a protein basis are complementary perspectives.

#### 5.4. Allocation

Herring filleting and lingonberry juice processing are multi-output processes handled by mass allocation. Mass allocation translates the value of herring or lingonberry as a resource regardless of the market price of its different products. As such, this allocation is in line with the essence of the CROSS process, which is the optimal utilization of marine resources. By handling these multi-output processes by mass allocation, upstream processes such as the impact of the transport of berry picking workers or the fuel used in fishing are brought to light, giving product developers awareness of the potential impacts associated with the raw materials used. Other approaches to handling these multi-output systems can also be used, such as allocation on an economic basis. Although not considered here, such analysis can be an interesting subject for future studies as they may further support the utilization of these co-products.

#### 5.5. Workforce transport

In this study we have considered the berry picking workforce travel from Europe or from Thailand to Sweden. These workers travel to Sweden exclusively for the purpose of picking berries. Workers employed by the fish processing industry are understood to be local workforce as we have no indication of the fisheries processing industries being dependent on a foreign workforce. Including flights of this type of seasonal workforce has been shown to be relevant for LCA for agricultural cases in the United Kingdom (Canals et al., 2008) and New Zealand (Mithraratne et al., 2010). Most importantly, for the specific case of lingonberries, a contribution analysis of the carbon footprint of the different stages in the life cycle, shows that up to the processing stage, the transport of workers was about two times that of the transport of the berries within Sweden or of the freezing (Sjoms, 2016). Additionally, the nature of the work differs, with berry picking being manual and labor-intensive, while fish processing into fillets in Sweden being a highly mechanized work, therefore, the exclusion of workforce travel except for the case of lingonberry is considered to be a pertinent modeling choice.

#### 5.6. Scaling up

In this study, a process developed in a laboratory is modeled at industrial scale. The input data for material quantities from experimental data was scaled up using literature. The energy consumption for the scaled up process was modeled using literature data together with estimations of processed volume and expert knowledge. For the input to the cross-processing, we note that since the ratio of fish and helper is

calculated on a dry weight basis, the total (wet) flowrates of the pomace, water, acid and base will vary depending on the moisture content of the helper and the fish co-products. Also, the amount of acid and base addition is depended on the speed of acid or base addition. Such variability is expected to have only a small effect on the final footprint of the protein ingredient and not cause significant changes in the overall message of this study. For the scaling up, knowledge of the process at an industrial scale was essential in this study, particularly in the determination of equipment type. While extraction of protein from fish cross-products via pH-shift is not commercially operational at this stage, the upscaled process uses equipment such as stirrers, homogenizers, and decanters which are standard in food processing industries. The volume stored and processed was estimated considering the availability of raw materials in Sweden, however as storage was the biggest consumer of energy, we see optimization of stored material as a promising focus for future environmental optimization of the full-scale process.

#### 5.7. Categories investigated

We have limited the analysis to climate change, energy, land occupation, and marine resources, which we considered a suitable set of categories to assess the CROSS process and its comparison with other options. A literature review of processed fish and seafood products which covered 69 LCA-related articles published across 20 different journals, presented 25 different indicators related to the fish biotic resource, sea use, nutritional and socioeconomic considerations (Ruiz-Salmón et al., 2021). In our study, we limited the fishery-specific resource impacts to the method provided by Hélias et al. (2018). Nonetheless, we recognize that other categories may also be of interest when investigating seafood systems. The fish stock depletion model we chose for this work has not yet been tested in much practical LCA work like this. We found it to be relatively straightforward to use but would like to see more publications applying this factor to a wider range of fish products.

The most important learning from using the method from Hélias et al. (2018) for marine resources was that discards had dominated the impact in this category, despite the relatively low discard rates used. For herring, different discard rates could be applied, e.g., by using discard rates for midwater pair trawl reported by Pérez Roda et al. (2019). However, the discard rate associated with this fishing gear is about four times the discard rate modeled, while the characterization factor of the modeled discard species is two orders of magnitude higher than the characterization factor of Atlantic herring. This first attempt to include discards in LCA demonstrates that, when quantifying stock depletion impacts, the species being discarded is of much greater importance than the choice of fishing equipment. Nevertheless, we note that discard rates used were based on average data and may not necessarily reflect specific cases in which selective gear is used, or recently implemented country or regional landing obligation policies.

Salmon aquaculture is a product system that we used for comparison. We modeled material and energy flows, but we did not investigate the local aspects of aquaculture. For example, local midpoint and endpoint impact categories for LCA of aquaculture have been developed, including the number of escaped salmon, lice outbreaks, area altered by aquacultural waste, and changes in nutrient concentrations in the aquatic environment (Ford et al., 2012).

The non-occupational use of forests during the lingonberry harvest has not been included. Here, only land occupation was investigated excluding, for example, differentiation between types and intensity such as built-up or arable land occupation. Additional analysis of terrestrial land use and its impact on biodiversity can also be relevant for the systems at hand and can be of further interest if data on lingonberry harvesting could be obtained.

## 6. Conclusion

Sustainable use of marine resources for direct human consumption has many facets. Here we explored one option which deals with food-grade handling of herring side streams followed by their pH-shift processing together with lingonberry pomace. Our study showed that the resulting CROSS-processing food product has a significantly lower potential impact on the environment than the compared options in terms of conserving marine resources. This approach to marine resource management will enable better utilization of resources for direct human consumption and reduced impacts compared to the business-as-usual route of fish side streams.

## CRediT authorship contribution statement

**Carla R.V. Coelho:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Gregory Peters:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Funding acquisition. **Jin-gnan Zhang:** Investigation, Writing – review & editing. **Mehdi Abdollahi:** Writing – review & editing, Supervision. **Ingrid Undeland:** Writing – review & editing, Supervision, Funding acquisition.

## 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.

## Data Availability

Data will be made available on request.

## Acknowledgments

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2022.106703](https://doi.org/10.1016/j.resconrec.2022.106703).

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