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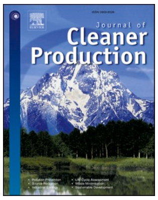

Identification of environmental hotspots in fishmeal and fish oil production towards the optimization of energy-related processes

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ABSTRACT

This study assessed the environmental impacts of a pelagic fishmeal and fish oil production plant in Iceland with the life cycle assessment methodology. The study focused on assessing the effects of different energy sources for utility production due to the high energy intensity of fishmeal and fish oil production, as quality improved with lower cooking temperature. The environmental hotspots of three different processing scenarios were assessed, where the factory was run on hydropower (*Scenario 0*), heavy fuel (*Scenario 1*) and a composition of both (*Scenario 2*), from cradle-to-factory gate. Midpoint results showed that the raw material acquisition contributed the most to the environmental impact when the fishmeal factory was operating on hydropower. However, drying had the highest impact when heavy fuel oil was used for utility production. This study also demonstrated that lowering the cooking temperature from 90 to 85 °C, led to improved quality and simultaneously reduced environmental impacts during processing. This indicated that a small energy adjustment in the production can have an environmental gain, demonstrating the necessity to optimize each processing step in the fishmeal and fish oil production process both for increased product quality and minimizing environmental impacts.

1. Introduction

Fishmeal and fish oils are considered the most nutritious and digestible ingredients for farmed fish and are increasingly being used in specific production stages of aquaculture (FAO, 2020). Cut-offs and small pelagic species used for fishmeal and fish oil production intended for feed and generally have lower quality and value than fish for direct human consumption (FAO, 2020). Moreover, as the fishmeal and fish oil production process is energy-intensive (Smárason et al., 2017), opportunities remain of producing higher-value products with less energy and lower environmental impact. In Iceland, the most commonly processed pelagic species are capelin (*Mallotus villosus*) and blue whiting (*Micromesistius poutassou*) (Statistics Iceland, 2019), which are generally processed directly to fishmeal and fish oil, along with cut-offs from Atlantic mackerel (*Scomber scombrus*) and Atlantic herring (*Clupea harengus*) fillet production (Statistics Iceland, 2019). Furthermore, fishmeal production may also include other small pelagic species and by-catch (FAO, 2020), causing high variations and heterogeneity of the final product. Although the high variation of the raw material can result in processing challenges, few improvements have been made to the fishmeal and -oil processes throughout the decades (FAO, 1986) but the market demand is changing, calling for improved knowledge and optimized processing methods in the fishmeal industry, both for higher nutritional value and economic value (Einarsson et al., 2019).

Current trends in market demand for higher quality fishmeal and fish oil, both for aquaculture feed and for direct human consumption (FAO, 2020), which calls for an increase in quality from optimized fishmeal and fish oil production processes. High temperatures applied in different processing steps have shown to result in negative quality effects due to protein and lipid denaturation (Thorkelsson et al., 2009). In response to this, Hilmarsdottir et al. (2020) showed that lowering the cooking temperature from 90 °C to 85 °C led to improvements in fishmeal and oil quality. While there is a need for higher quality fishmeal products, there is also increased demand for environmentally sustainable products to minimize their environmental impacts. In fishmeal and fish oil production, the highest energy use occurs during cooking and drying (Smárason et al., 2017), which indicates that optimizing these processing steps could reduce the environmental impact of fishmeal and oil

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processing. Thus, assessing the environmental impact of process optimizations are an important step towards increased sustainability of the production.

When exploring literature assessing the environmental impacts of fishmeal and fish oil production, few studies can be found. The most relevant study assesses the environmental sustainability of fishmeal and fish oil factories in Peru with life-cycle assessment (LCA). Fréon et al. (2017)) concluded that to decrease the environmental impact of the Peruvian fishmeal industry, which included the use of natural gas instead of heavy fuel oil, modernization of the oldest processing plants, and production of higher quality fishmeal was necessary. Moreover, recommendations included an assessment of different energy sources used for operating the fishmeal factories (Fréon et al., 2017). The different energy sources affect the high global warming impacts connected to unsustainable energy sources and most other impact categories. Furthermore, the energy used to operate the fishmeal plants had the highest environmental contribution when comparing the usage, construction, and maintenance of the fishmeal and fish oil factories (Fréon et al., 2017).

Improving the primary production phase and feed sourcing practices have been reported to return the highest environmental improvement in the supply chain of exported, frozen tilapia products (Pelletier and Tyedmers, 2010). Hence, the supply chain, starting from raw material acquisition to all steps of the production process of fishmeal and fish oil, was investigated in the current study. Analyses of the literature revealed that assessment of environmental sustainability of fishmeal and fish oil production are generally assessed as part of other product supply chains, such as aquaculture feed. (Samuel-Fitwi et al., 2013) compared the impacts of different fishmeals in aquafeed, and the study showed that replacing trout feed with soy or rapeseed meal reduced global warming by 40% and acidification by 25%. This is among others due to the high energy intensity of fishmeal production. Crop-derived feed inputs are then reported to be less impactful than fish-based inputs (Pelletier and Tyedmers, 2010). Other potential means to reduce the environmental impact of aquafeed include increasing the feed efficiency, such as using fishmeal from by-products from other processes instead of using fish directly caught for aquafeed applications (Papatryphon et al., 2004). Furthermore, recycling nutrients has been reported as one of the key roles in improving environmental performance in aquaculture (Pelletier and Tyedmers, 2010), lowering stressing the importance of using fish industry side-streams and by-products for fishmeal and fish oil production.

Energy usage within the fishmeal and fish oil factories has not yet been studied thoroughly, although rough fuel consumption estimates during fishmeal production (FAO, 1986) and raw material acquisition in Norway (Schau et al., 2009) are available. As quality is the driving force of each product, process adjustment resulting in a higher value product, such as lowering the cooking temperature (Hilmarsdottir et al., 2020), could benefit the environment. In addition to lower heat-treatment during fishmeal and fish oil processing, the usage of green energy sources and fossil-based energy sources has not yet been compared, although there is a potential for a sustainable solution and hence, cleaner production.

In Europe, most fishmeal factories operate partially or totally on heavy fuel oil, while in Iceland, most factories are fuelled with greener energy sources, such as hydropower, or a mix of fossil-based and green energy (Table 1). Given the fact that fishmeal production is energy-intensive, opportunities lie in changing their energy source for environmental gains. Due to the strong influence of the energy sources chosen during the operational time of the fishmeal and fish oil plants, decreasing the cooking temperature by 5 °C, in addition to hotspot analysis, would give a clearer view of the processing steps needing optimization (Hilmarsdottir et al., 2020). As the fishmeal and fish oil production process is energy-intensive (Smárason et al., 2017), from 265 to 576 kg CO_2 eq per 1 tonne fishmeal (Fréon et al., 2017), a relatively small adjustment within the energy usage of the factory could result in a significant environmental gain, even with simple solutions that require small investments (Thrane et al., 2009). Moreover, before changing the production process drastically, it is necessary to identify the future optimization potential of the fishmeal plants. As the fishmeal production process needs optimization, investigating the changes at an early stage of the development by applying a life cycle assessment (LCA) is highly recommended (Ögmundarson et al., 2020), prioritizing the processes that require optimization. A concurrent increase in product quality needs to be secured, making this an iterative process where product quality and environmental sustainability go hand in hand.

Table 1
Fuel types used in the fishmeal and fish oil industry in 2019, depending on the country. Factories can operate on more than one fuel type. The table is adapted and updated from (EUfishmeal, 2019).

Country	Factories	Electricity	Oil	Gas	Other
Iceland	10	5	5		
Norway	6		4	3	1 (LPG)
Denmark	3			3	1 (Coal)
UK	3		1	2	
France	2				2 (External Power)
Faroe Island	2		2		
Germany	1			1	
Ireland	1		1		
Finland	1		1		
Total	**29**	**5**	**14**	**9**	**4**

The main goal of this study was to assess the environmental impacts of fishmeal and fish oil production from the cradle-to-factory gate. This research identifies the environmental benefits of energy adjustment during production processes in a fishmeal and oil factory in Iceland. A hotspot analysis was conducted on this base case to identify the future optimization potential of the analyzed fishmeal and fish oil production process. The potential environmental benefits of changing the energy sources from heavy fuel oil to hydropower were also investigated, as most European countries still operate on heavy fuel oil (Table 1) (EUfishmeal, 2019).

2. Materials and methods

The framework followed in the current study was in accordance to International Standard Organization (ISO) 14040 (ISO, 2006, p. 14040) and 14044 (ISO, 2006, p. 14044) and addressed the four mandatory steps when conducting an LCA study; the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase (Hauschild et al., 2017). In addition, calculations of the mass and energy flow of the production process gave estimations of the energy and power consumption, where the samples used to build the mass balance were collected first-hand.

2.1. Research objectives

This study aimed to:

1) assess the environmental impacts of fishmeal and fish oil production from cradle-to-gate with a focus on energy sources,
2) identify the environmental benefits of energy adjustments during processing steps while increasing product quality,
3) identify future optimization potentials of the fishmeal and fish oil production process by using hotspot analysis, and
4) provide a detailed life cycle inventory (LCI), which aims to link all unit processes required to produce the fishmeal and fish oil.

The functional unit assessed was “the production of 1000 kg of pelagic fishmeal including fish oil from cradle to factory gate, produced in Iceland in 2018” and included three scenarios depending on theoretical application of different energy sources during the production of fishmeal and fish oil.

2.2. The fishmeal and fish oil process description

An overview of a traditional pelagic fishmeal and fish oil process with an average of 1200 tonnes of raw material entering the production each day can be seen in Fig. 1. The raw materials entered a preheating step (55 °C for 20 min), which used excess energy from the steam-drier and the evaporators to lower the energy cost (Einarsson et al., 2019). Then, the raw materials were cooked (at 90 °C for 20 min) and drained for water removal. The resulting liquid stream was treated with a decanter to remove the remaining solids and concentrated further. Oil was recovered from the liquid stream through three centrifuges, and the solid streams, which were obtained from the press, decanter, and evaporators, were mixed during the initial drying steps. The steam-drying included a rotary disc steam dryer lowering the water content to 40%, by applying a steam temperature of 160 °C and a drying temperature of 95 °C for 25–35 min. The air dryer used was a Hetland air dryer, which decreased the water content to 5–10% water, with input air at 450 °C, although having 150 °C in the middle of the dryer.

Samples were collected during a steady-state of the production line and cooled overnight at 0 ± 2 °C, followed by transport to the laboratory where it was kept at −25 °C until further analysis. Analyzing the samples took up to seven months after collection, and all samples were measured in triplicates.

2.3. Data collection and system modeling

2.3.1. Energy use during raw material acquisition

The energy usage at sea during fishing of the studied pelagic species was estimated as the average energy use for all trips from one trawler during the capelin fishing season in 2018. The ratio between sailing towards the catching ground, fishing and chilling, and sailing back to shore was compared and aligned with the annual energy consumption. The fishing vessel assessed was one of the younger fishing vessels in the Icelandic pelagic fishing fleet (from 2014). Hence, the energy usage during the raw material acquisition at sea might be underestimated in the current study as the average fishing vessel age in the Icelandic fishing fleet is currently around 21 years old (The Directorate of Fisheries, 2020).

2.3.2. Mass and energy balances during fishmeal and fish oil processing

Samples from each processing step in the fishmeal and fish oil production were collected and analyzed for water and lipid content, and the remaining material expressed as fat-free dry matter (FFDM) during the production of fishmeal and fish oil from capelin (C), a blend of mackerel and herring (MHB) and blue whiting (BW), respectively. However, during the blue whiting (BW) production, data included only first-hand chemical composition results from the raw material, press (liquid and cake), separate press liquid, sludge, concentrate, fishmeal and fish oil. Other sampling locations were modeled according to the capelin production, as the BW production was expected to perform in a similar way due to similar lipid content of capelin and blue whiting.

The mass balances during the fishmeal and oil productions were set up and modeled through gathered data on the total mass, water, lipid and fat-free dry matter (FFDM) composition at each sampling location for the three different pelagic species (Hilmarsdottir et al., 2021), and at different cooking temperatures (Hilmarsdottir et al., 2020). A functional production unit of 1000 kg fishmeal and fish oil was assumed in each scenario. The quantity of each processing stream was modeled during production of C and MHB, as well as at a few key sampling places during production of BW as mentioned earlier. The energy consumption of each processing step was calculated based on the mass flow and balances along with known heat transfer equations explained in both Fellows (2000) and Geankoplis (1993) during the fishmeal and fish oil (kW) production from the different species and at the different cooking temperatures. The time during each processing step was then included in the assessment of the power consumption (kWh) of each processing step. All calculated values were aligned with documented energy and power usage from the company's open green reports for 2018 (Síldarvinnslan, 2018). The obtained modeled power values were used in the following LCA calculations.

The preheating and draining steps were not considered in the LCA calculations as excess energy from the steam dryer and the evaporators were used for the preheating, and draining does not require energy as it is a sieving process.

The annual use in 2018 of chemical agents, materials and energy per functional production unit (1000 kg fishmeal) are open to the public by the Environment Agency of Iceland stated (Síldarvinnslan, 2018). Staff members from the fishmeal and fish oil plant studied estimated annual reparations of the fishing gear used during capelin fishing, used in the raw material acquisition.

2.4. LCA system boundaries

For a successful life cycle assessment, it was necessary to define the system boundaries and which variables were included in the assessment (Fig. 2). In the current study, the system boundaries were defined to include the catching of the capelin raw material, emissions, and energy use on the trawlers (sailing towards the catching ground, during catching and superchilling, and sailing towards shore), as well as the mass of raw materials entering the fishmeal and fish oil production process on land (Raw material acquisition). Fishing gear and other material usages on board were inside the system boundaries and included the use of nylon, hydraulic fracturing fluid, lubricating oil, and fuel (heavy fuel oil) (see *Appendix,* Table A.1*)*.

As the assessed fishmeal and fish oil plant studied is almost 50 years old, and it is estimated that around 1.2 million tonnes of fishmeal have been produced during its lifetime to date, it was assumed that including the plant itself was negligible. Hence, the construction of the fishmeal and fish oil facilities were considered outside the system boundaries. Cleaning, waste and maintenance were assessed within the system boundary.

The backup energy generator was assumed to power the whole fishmeal and fish oil production process for short periods (Síldarvinnslan, 2018), e.g. during bad weather conditions. However, if the energy

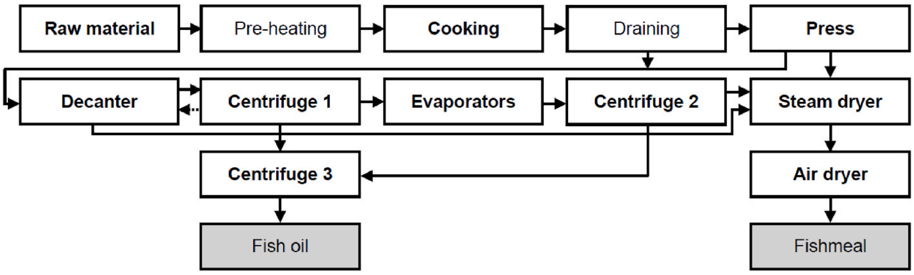


Fig. 1. A traditional fishmeal and fish oil production process. (Hilmarsdottir et al., 2020).

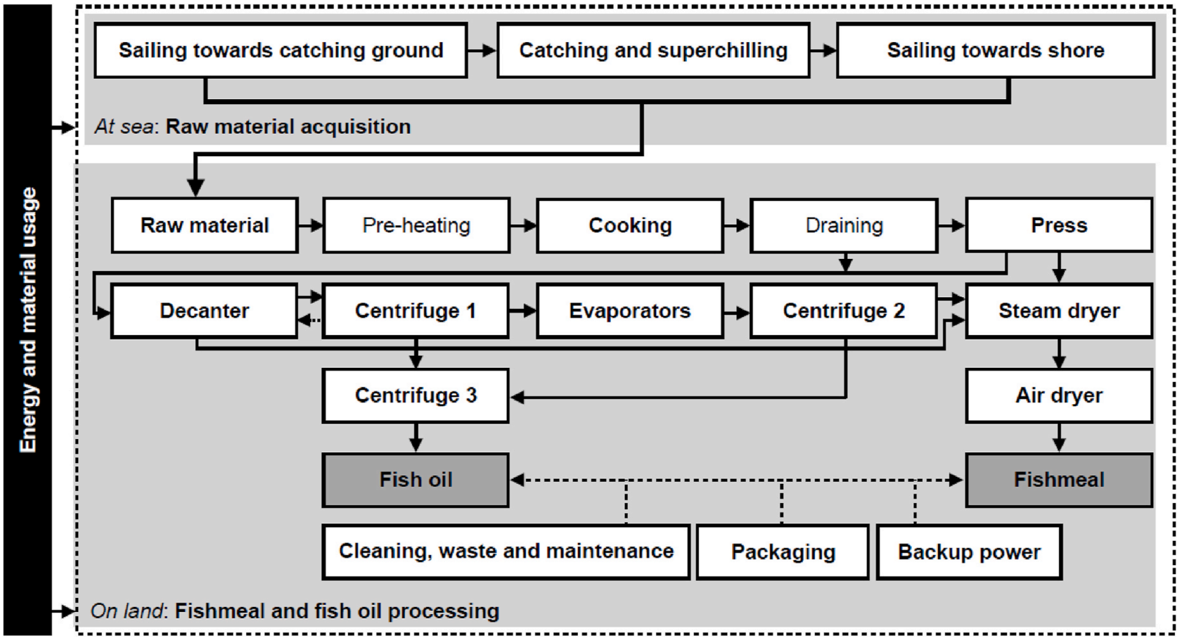


Fig. 2. Process flow of the production system, identifying the system boundaries of the life cycle assessment during production of 1000 kg of pelagic fishmeal, including fish oil from cradle to factory gate, in Iceland in 2018.

consumption of the generator was distributed evenly during processing, the heavy fuel oil impact would be lost, and was hence assigned as a separate process step.

2.5. Life cycle impact assessment (LCIA)

The Life Cycle Assessment (LCA) calculations were modeled with the SimaPro version 9.1.0.8 software (PReConsultants, Amersfoort, Netherlands) in connection to the ecoinvent 3.6 life cycle inventory. SimaPro modeled from the average energy of the functional unit, products and chemicals used at each step within the system boundary (Fig. 2). In the current study, the impact assessment method used was midpoint level ReCiPe 2016. The following impact categories were included in the assessment: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, human toxicity, fine particulate matter impacts, tropospheric ozone formation, acidification, eutrophication, ecotoxicity, land use, resources depletion, and water consumption. Midpoint impact categories were used to identify environmental hotspots across different life cycle stages and identifying the most contributing mass and energy inputs and outputs at each production step (Ögmundarson et al., 2020), which has effectively been applied earlier to evaluate the impact of variating protein sources in aquafeed (Samuel-Fitwi et al., 2013).

2.6. Analyzed energy source scenarios

Three energy source scenarios were modeled and analyzed in this study. For all scenarios, the same raw material acquisition was included. The energy source in Scenario 0 was 100% hydropower. As the assessed fishmeal and fish oil production factory was in 2018 the only known fishmeal plant operating on 100% hydropower worldwide, two different scenarios were also set up to assess the effects of fuel choice on the environmental impact of the production process. Hence, two scenarios were added to assess the most common energy source in European fishmeal and fish oil factories (Table 1), and the average energy source combination of Icelandic fishmeal and fish oil factories according to the Icelandic Union of Fishmeal factories (see Appendix, Table A.1). Scenario 1 thus only ran on heavy fuel oil, and Scenario 2 with a combination of 24.6% heavy fuel oil and 75.4% hydropower. The energy was measured in kWh in all three scenarios.

2.7. Uncertainty and sensitivity

The uncertainty of the assessment results was calculated by performing a Monte Carlo simulation using a Pedigree matrix approach (Hauschild et al., 2017). The predefined uncertainty factories in ecoinvent 3.6 were used, except for acetic acid, which was manually added as it was missing in the ecoinvent 3.6 databases (see Appendix, Fig. A.1). The number of simulations performed in the Monte Carlo simulation was 5000 runs to assess the 2.5%–97.5% confidence intervals of the results.

Five sensitivity scenarios were identified to evaluate the sensitivity of the results to changes in the system modeling and settings, as summarised in Table 2. The sensitivity level included various potentially influencing factors during raw material acquisition and fishmeal and fish oil production.

Oil usage during raw material acquisition differs on various factors such as the vessel's age, time spent on the ocean, different captains,

Table 2
Sensitivity scenarios at different processing steps when producing 1000 kg of fishmeal, including fish oil.

Sensitivity scenario	Scenario description
Raw material acquisition	• Different fishing gear applied, weather conditions, catch size, time spent on the ocean, captain
The fishmeal and fish oil processing	• Depending on the freshness of the raw material, water content could fluctuate (depending on catch and species), and hence the drying steps differ in time and energy • During cooking, the raw material can be heterogeneous and differ in freshness, and the breakdown of the raw material can hence be affected. If the raw material is too fresh, it can be difficult to process • During evaporation, the number of solid particles in the evaporation can differ, affecting the viscosity of the streams • Cleaning agents might be difficult to monitor and different depending on fishmeal factories. Moreover, other cleaning agents might be used in different scenarios.

catch size, trawling time, and weather conditions (Table 2). Hence, the average oil usage during seven fishing trips from one fishing vessel was applied in the calculations. During these fishing trips the fishing vessel was operated with only two captains and during the same season to keep the variations at minimum.

The raw material entering the fishmeal and fish oil production plant can variate in various factors of the raw materials, including variations in water, lipids and other chemical composition factors (Hilmarsdottir et al., 2020), including seasonal variation (Romotowska et al., 2016) (Table 3). Those factors affect the efficiency of the processing steps, e.g., the drying can differ in time and energy depending on the water content. According to the staff members operating the studied fishmeal factory, processes oriented towards homogenizing the material depend on the freshness of the raw material, where too fresh raw material can be more viscous than older raw material and hence, difficult to handle. Evaporation could also increase viscosity due to variate amounts of solid particles in the stream (Hall, 2010). Cleaning agents can variate between years and processing plants, but the amount of chemicals used is not closely monitored. Moreover, it is assumed that the fishmeal and fish oil production plants do not save chemical cleaning agents when it comes to cleaning due to the strict regulations regarding hygienic standards.

2.8. Statistical analysis

Statistical analyses were performed in Microsoft Office 365 with Excel (Microsoft, Redmond, WA, USA). Results were shown as mean values ± standard deviation (SD), and the significance level was set to $p < 0.05$ to prove with 95% certainty if the theory being investigated was significant or not due to change. This level of significance is commonly used for the assessment of biological processes such as those encountered during food and feed production.

3. Results and discussion

3.1. Midpoint analysis of the raw material acquisition

The midpoint analysis results of the raw material acquisition can be seen in Table 4. This life cycle stage was divided into three different substages, as is commonly done by the industry to assess monetary costs related to fishing. The substages were divided into i) sailing towards catching ground, ii) catching and superchilling of the catch, and iii) sailing towards shore. The raw material acquisition was identical for all three scenarios studied (see section 2.6). A hotspot analysis identified which of the life cycle stages of the raw material acquisition contributed most to each impact category. The highest contributing process was burning heavy fuel oil (diesel) to motor the fishing vessel, where sailing towards the shore was the most energy-intensive part of the raw material acquisition.

Table 3
Sensitivity scenarios at different processing steps when producing 1 tonne of fishmeal, including fish oil.

Sensitivity scenario	Scenario description
Raw material acquisition	Different fishing gear applied, weather conditions, catch size, time spent on the ocean, captain
The fishmeal and fish oil processing	Depending on the freshness of the raw material, water content could fluctuate (depending on catch and species), and hence the drying steps differ in time and energy During cooking, the raw material can be heterogeneous and differ in freshness, and the breakdown of the raw material can hence be affected. If the raw material is too fresh, it can be difficult to process During evaporation, the number of solid particles in the evaporation can differ, affecting the viscosity of the streams Cleaning agents might be difficult to monitor and different depending on fishmeal factories. Moreover, other cleaning agents might be used in different scenarios.

During the raw material acquisition at sea (Fig. 2), most of the fuel was spent sailing towards shore with the catch, or on average, 44 ± 13% of the total fuel usage (Table 4). A significant difference in fuel usage was also identified when analyzing the different fishing gear used when catching and superchilling capelin. Using a purse seiner resulted in lower average fuel use (17 ± 7% of the total fuel usage) than trawling (31 ± 4% of the total fuel usage). However, sailing towards shore did not result in a significant difference, despite the resistance of the water during trawling. For the fishing trips, see details in Appendix, Table A.3.

The effect of different fishing gear and fuel usage has been studied before, but high variations can be seen in fuel usage, according to the chosen fishing gear, origin of catch and species caught Trawling is for example generally considered more energy-intensive compared to purse seiner (Schau et al., 2009). Cashion et al. (2017) estimated a carbon dioxide equivalent release of 1.34 $CO_{2\ eq}$ per 1000 kg of capelin (Mallotus villosus) caught with a pelagic trawl. In the current study, the total impact results on global warming were 3.2×10^2 $CO_{2\ eq}$ during catching of capelin, producing 1000 kg of fishmeal and fish oil, which was higher than expected. However, indications towards the purse seiner having a lower carbon footprint than the trawl were observed in both studies (Cashion et al., 2017). Moreover, the fuel use differed significantly between fishing gear in the current study (Table 5) and can be seen in detail in Appendix, Table A.2).

3.2. Power usage analysis of the fishmeal and fish oil processing

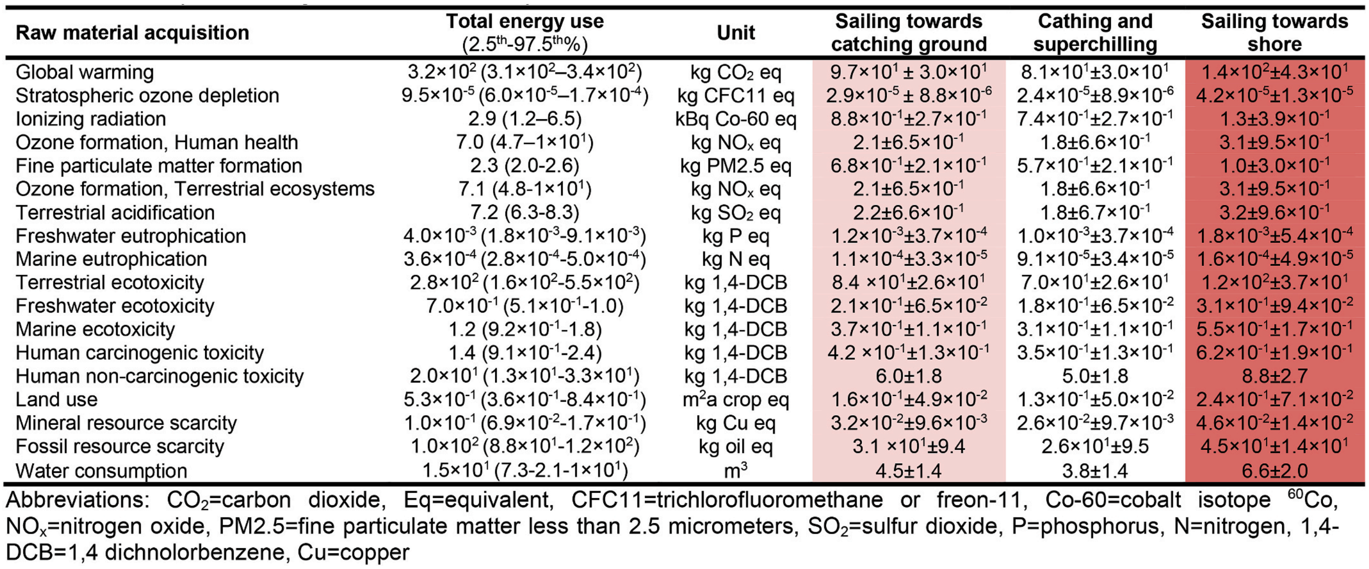
The mass and energy flow was obtained from chemical composition results from all processing step during the capelin and mackerel/herring blend fishmeal productions, and from key processing locations in the blue whiting fishmeal production. The mass and energy flow from the draining, slurry, stickwater, separated press oil, centrifuged oil, and the latter concentrate were modeled for the blue whiting. The quantity of each process stream was modeled to fit the functional production unit of 1000 kg of fishmeal in each process (modeled values are expressed in italic font in Fig. 3).

The energy usage was calculated from the mass balance, and as different inputs of raw material entered the process, the energy differs between the species processed. The capacity of the steam separator connected to the evaporator was 4.5 tonnes per hour, and hence the energy was calculated on an hourly basis. Next, the annual power consumption per 1000 kg fishmeal and fish oil, from the studied company (Síldarvinnslan, 2018) was aligned with the calculated values where the production was estimated to run for 3 h on average per day. The power to heat the raw material from preheating (50 °C) to 85 °C was compared to the effects of the 90 °C heating during cooking, which affected the power ratio of each processing step (Table 6). The preheating step was not included in the power and energy calculations of the functional unit, as excess steam from the evaporators and the steam dryer was recycled to heat the raw materials from an ambient temperature to approximately 50 °C. The capacity of the steam separator in the evaporator and the amount of raw materials hence, variated.

The processing steps are displayed in Table 6. The drying steps consumed the most energy (see Appendix, Table A.4), followed by evaporation, pressing, decanters, cookers, and centrifuges. During the production of fishmeal and fish oil, the power difference using 85 °C in the cookers instead of 90 °C was lowered by 11–12% during cooking, resulting in different energy distribution among the processing steps overall (Table 6). The power consumption in each step in kWh is summarised in Appendix, Table A.5.

The average overall fishmeal yield in the fishmeal and fish oil production company studied was 18.5% and 5.7%, respectively, in 2018 according to calculations from the green accounting reports and ranged from 16 to 20%, while the fish oil yield ranged between 0.5 and 17%, depending on the season and catch (Table 6).

Table 4
Midpoint analysis of the energy use during raw material acquisition at sea, and their contribution to each impact category. Darker colours represent a higher environmental impact.



Raw material acquisition	Total energy use (2.5th-97.5th%)	Unit	Sailing towards catching ground	Cathing and superchilling	Sailing towards shore
Global warming	3.2×10^{2} (3.1×10^{2}–3.4×10^{2})	kg CO_2 eq	$9.7\times10^{1} \pm 3.0\times10^{1}$	$8.1\times10^{1}\pm3.0\times10^{1}$	$1.4\times10^{2}\pm4.3\times10^{1}$
Stratospheric ozone depletion	9.5×10^{-5} (6.0×10^{-5}–1.7×10^{-4})	kg CFC11 eq	$2.9\times10^{-5} \pm 8.8\times10^{-6}$	$2.4\times10^{-5}\pm8.9\times10^{-6}$	$4.2\times10^{-5}\pm1.3\times10^{-5}$
Ionizing radiation	2.9 (1.2–6.5)	kBq Co-60 eq	$8.8\times10^{-1}\pm2.7\times10^{-1}$	$7.4\times10^{-1}\pm2.7\times10^{-1}$	$1.3\pm3.9\times10^{-1}$
Ozone formation, Human health	7.0 (4.7–1×10^{1})	kg NO_x eq	$2.1\pm6.5\times10^{-1}$	$1.8\pm6.6\times10^{-1}$	$3.1\pm9.5\times10^{-1}$
Fine particulate matter formation	2.3 (2.0-2.6)	kg PM2.5 eq	$6.8\times10^{-1}\pm2.1\times10^{-1}$	$5.7\times10^{-1}\pm2.1\times10^{-1}$	$1.0\pm3.0\times10^{-1}$
Ozone formation, Terrestrial ecosystems	7.1 (4.8-1×10^{1})	kg NO_x eq	$2.1\pm6.5\times10^{-1}$	$1.8\pm6.6\times10^{-1}$	$3.1\pm9.5\times10^{-1}$
Terrestrial acidification	7.2 (6.3-8.3)	kg SO_2 eq	$2.2\pm6.6\times10^{-1}$	$1.8\pm6.7\times10^{-1}$	$3.2\pm9.6\times10^{-1}$
Freshwater eutrophication	4.0×10^{-3} (1.8×10^{-3}-9.1×10^{-3})	kg P eq	$1.2\times10^{-3}\pm3.7\times10^{-4}$	$1.0\times10^{-3}\pm3.7\times10^{-4}$	$1.8\times10^{-3}\pm5.4\times10^{-4}$
Marine eutrophication	3.6×10^{-4} (2.8×10^{-4}-5.0×10^{-4})	kg N eq	$1.1\times10^{-4}\pm3.3\times10^{-5}$	$9.1\times10^{-5}\pm3.4\times10^{-5}$	$1.6\times10^{-4}\pm4.9\times10^{-5}$
Terrestrial ecotoxicity	2.8×10^{2} (1.6×10^{2}-5.5×10^{2})	kg 1,4-DCB	$8.4 \times10^{1}\pm2.6\times10^{1}$	$7.0\times10^{1}\pm2.6\times10^{1}$	$1.2\times10^{2}\pm3.7\times10^{1}$
Freshwater ecotoxicity	7.0×10^{-1} (5.1×10^{-1}-1.0)	kg 1,4-DCB	$2.1\times10^{-1}\pm6.5\times10^{-2}$	$1.8\times10^{-1}\pm6.5\times10^{-2}$	$3.1\times10^{-1}\pm9.4\times10^{-2}$
Marine ecotoxicity	1.2 (9.2×10^{-1}-1.8)	kg 1,4-DCB	$3.7\times10^{-1}\pm1.1\times10^{-1}$	$3.1\times10^{-1}\pm1.1\times10^{-1}$	$5.5\times10^{-1}\pm1.7\times10^{-1}$
Human carcinogenic toxicity	1.4 (9.1×10^{-1}-2.4)	kg 1,4-DCB	$4.2 \times10^{-1}\pm1.3\times10^{-1}$	$3.5\times10^{-1}\pm1.3\times10^{-1}$	$6.2\times10^{-1}\pm1.9\times10^{-1}$
Human non-carcinogenic toxicity	2.0×10^{1} (1.3×10^{1}-3.3×10^{1})	kg 1,4-DCB	6.0 ± 1.8	5.0 ± 1.8	8.8 ± 2.7
Land use	5.3×10^{-1} (3.6×10^{-1}-8.4×10^{-1})	m^2a crop eq	$1.6\times10^{-1}\pm4.9\times10^{-2}$	$1.3\times10^{-1}\pm5.0\times10^{-2}$	$2.4\times10^{-1}\pm7.1\times10^{-2}$
Mineral resource scarcity	1.0×10^{-1} (6.9×10^{-2}-1.7×10^{-1})	kg Cu eq	$3.2\times10^{-2}\pm9.6\times10^{-3}$	$2.6\times10^{-2}\pm9.7\times10^{-3}$	$4.6\times10^{-2}\pm1.4\times10^{-2}$
Fossil resource scarcity	1.0×10^{2} (8.8×10^{1}-1.2×10^{2})	kg oil eq	$3.1 \times10^{1}\pm9.4$	$2.6\times10^{1}\pm9.5$	$4.5\times10^{1}\pm1.4\times10^{1}$
Water consumption	1.5×10^{1} (7.3-2.1-1×10^{1})	m^3	4.5 ± 1.4	3.8 ± 1.4	6.6 ± 2.0

Abbreviations: CO_2=carbon dioxide, Eq=equivalent, CFC11=trichlorofluoromethane or freon-11, Co-60=cobalt isotope ^{60}Co, NO_x=nitrogen oxide, PM2.5=fine particulate matter less than 2.5 micrometers, SO_2=sulfur dioxide, P=phosphorus, N=nitrogen, 1,4-DCB=1,4 dichnolorbenzene, Cu=copper

Table 5
Results from fuel usage and time spent on the ocean when catching capelin in 2018 using two different fishing gears.

Dates from capelin catching from one vessel in 2018	Fuel usage			Time		
	Sailing towards catching ground	Catching and superchilling	Sailing towards shore	Sailing towards catching ground	Catching and superchilling	Sailing towards shore
Average fuel and time with trawl	30 ± 3%	**31 ± 4%**[a]	39 ± 6%	19 ± 7%	69 ± 5%	11 ± 2%
Average fuel and time with purse seiner	31 ± 15%	**17 ± 7%**[b]	52 ± 18%	25 ± 11%	60 ± 13%	15 ± 14%
Overal average fuel and time	30 ± 9%	25 ± 9%	44 ± 13%	22 ± 9%	65 ± 10%	13 ± 8%

Similar power usage has been reported by Hall (2010) during fishmeal and fish oil production. The power usage during cooking, evaporation and drying were compared between the studies, as information on other steps were lacking (Hall, 2010). The comparison indicated higher power usage during evaporation, or 52% of the total energy, whereas, in the current study, evaporation accounted for 16–21% of the total power consumption. Cooking accounted for 4.5–7% of the total energy in the current finding, while cooking accounted for 10% in the study by (Hall, 2010). Moreover, drying accounted for 46–55% in the current study, while 38% was reported by (Hall, 2010). However, the current energy usage was estimated into power due to the different operating times of each operation, followed by an estimation of operating time per day. The power usage for other processing steps (excluding cookers, evaporators and dryers) during March 2018 was 564 kWh. However, when power estimations (kWh) obtained from green accounting reports of annual usage were aligned with the mass flow, the factory was estimated to operate for 6 h per day on average in 2018.

3.3. *Midpoint analysis of different energy source scenarios*

Different trends were noticed in the midpoint analysis results on which processing steps affect the different impact categories depending on the energy source in each of the Scenarios (Fig. 3). Energy-related processes affected the impact categories less in Scenario 0 compared to the other scenarios. Therefore, cleaning agents, waste and maintenance resulted in the highest environmental impact in most of the impact categories in Scenario 0. Furthermore, the ratio of cleaning agents, waste and maintenance was higher than all other processing steps combined in stratospheric ozone depletion, ionizing radiation, fine particulate matter formation, terrestrial acidification, freshwater- and marine eutrophication, freshwater- and marine ecotoxicity, human non-carcinogenic toxicity, land use, and fossil resource scarcity.

Analysis of the heavy fuel oil-driven fishmeal and fish oil production process (Scenario 1) showed that cleaning, waste, and maintenance remained highest in freshwater- and marine eutrophication, freshwater ecotoxicity, and water consumption, emphasizing the environmental gain of operating the fishmeal and fish oil factory on hydropower instead of fossil fuels (Fig. 3). Combined drying steps accounted for the highest 54%, evaporation highest 16%, cooking up to 5%, and other processes combined up to 7% of the total environmental impact in each impact category. Similar to Scenario 0, combined drying steps accounted for 54% of global warming, followed by evaporation (16%), while cleaning, waste, and maintenance accounted for 2%.

In Scenario 2, analysis of the fishmeal and fish oil process operated partially on hydropower (75.4%) and partially on heavy fuel oil (24.6%) resulted in similar trends as in Scenario 0 and Scenario 1 (Fig. 4). Freshwater- and marine eutrophication, and freshwater ecotoxicity remained the highest environmental contributors during cleaning, waste and maintenance as in the other Scenarios, where the drying steps remained the environmental contributors in global warming (51%) followed by evaporation (15%), while 5% resulted from cleaning, waste, and maintenance, as in Scenario 1.

3.3.1. *Optimization of the cooking step during fishmeal and fish oil processing*

The environmental benefits of lowering the cooking temperature

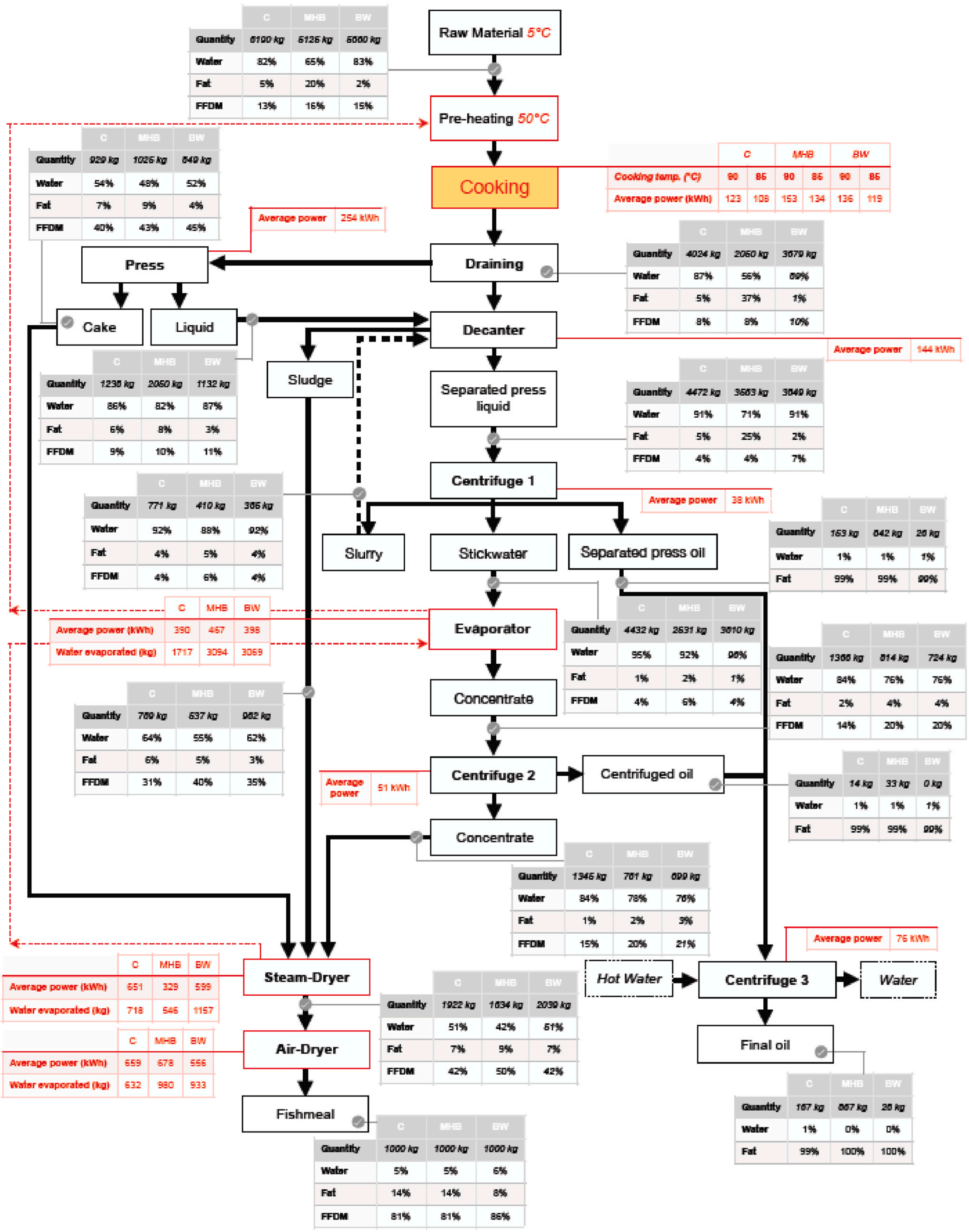


Fig. 3. Flowchart of the investigated traditional fishmeal and fish oil production process, including mass and energy balances of 1000 kg of fishmeal and fish oil production from capelin (C), a blend of mackerel and herring cut offs (MHB), and blue whiting (BW). Measured values were water, lipids and fat free dry matter (FFDM) and applied power (kWh) and water evaporated (kg) modeled for 90 °C cooking temperature and presented with red color. Dashed lines indicate reused stream and italic letters modeled values.

Table 6
Power usage at each processing step of the total power consumption during fishmeal and fish oil production at 90 °C and 85 °C cooking temperature, respectively. Fishmeal and fish oil yield percentages were calculated.

Power usage of processing steps (% of total energy)	Capelin		Mackerel/herring blend		Blue whiting	
	90 °C	85 °C	90 °C	85 °C	90 °C	85 °C
Cookers	5.1	4.5	7.0	6.2	6.0	5.3
Presses	10.7		11.6–11.7		11.3–11.4	
Decanters	6.0–6.1		6.6		6.4	
Centrifuges 1	1.6		1.7–1.8		1.7	
Evaporator	16.3–16.5		21.3–21.5		17.7–17.8	
Centrifuges 2	2.1		2.3		2.3	
Steam dryer	27.3–27.4		15.0–15.1		26.6–26.8	
Air dryer	27.8		31.2		24.8	
Centrifuges 3	3.2		3.5		3.4	
Fishmeal yield	16%		20%		18%	
Fish oil yield	3%		17%		0.5%	

from 90 °C to 85 °C were analyzed based on a higher quality of the fishmeal obtained at 85 °C (Hilmarsdottir et al., 2020). While the increased physicochemical quality in the fishmeal was tested and presented in Hilmarsdottir et al. (2020), no studies have estimated the environmental impact of changing the cooking temperature during fishmeal and oil processing.

The overall gain by decreasing the cooking temperature from 90 °C to 85 °C, in each Scenario can be seen in Table 7. The highest gain over all the impact categories was observed in Scenario 1 (heavy fuel oil), where 4.6 kg CO_2 eq was saved by the temperature reduction, or 0.6% of global warming impact the production. If capelin caught in Iceland in 2018 accounted for 186 000 tonnes (The Marine and Freshwater Research Institute, 2019), 205 kg CO_2 eq would thus be saved annually if all fishmeal and fish oil factories in Iceland would decrease their cooking temperature from 90 °C to 85 °C during the capelin season (Scenario 2).

Reducing the cooking temperature resulted in an overall environmental gain in all energy sources studied, and higher quality fishmeal and fish oil (Hilmarsdottir et al., 2020). Therefore, a cooking temperature of 85 °C instead of 90 °C is proposed for all studied species and energy source scenarios. Until recently, common practice has been 90–95 °C (FAO, 1986). However, heating above 75 °C has not resulted in a higher fat separation (FAO, 1986), and moreover, improved fat separation in capelin has been reported at 70–80 °C (Nygaard, 2010). Parallel to environmental gain with lower temperatures, less overheating is assumed, resulting in higher quality products. A reduction in the use of cleaning agents can also be assumed as the energy efficiency during cooking can be increased if product build-up on processing equipment surfaces due to overheating can be minimized (Hall, 2010). Therefore, an investigation into fishmeal and fish oil quality and their environmental impact at lower temperatures could be subject for a follow-up study.

3.4. *Midpoint analysis of the effect of cleaning, waste and maintenance*

Midpoint analysis on the production processes showed that the evaporation, drying steps, and cleaning, waste and maintenance, had the highest environmental impacts across all energy sources studied. Fuel use has been reported to dominate climate change (87%) during fishmeal and fish oil production (Fréon et al., 2017), while higher emphasis should also be on chemical agents.

The overall highest impact from the cleaning agents, waste and maintenance, came from the use of acetic acid, followed by sodium hydroxide usage in all impact categories, except for nitric acid having the highest impact on the stratospheric ozone depletion (80%), and municipal solid waste on the marine eutrophication (Table 8). Other processes included iron scrap, formaldehyde, hydrochloric acid, and sodium hypochlorite, which impact was below 6% in all impact categories. Cleaning, waste and maintenance remained the same in all Scenarios.

3.5. *Hotspot analysis of different fuel source scenarios*

Analysis of midpoint evaluation in Scenario 0 (Table 9), fishmeal and fish oil production operated entirely on hydropower, showed that most environmental impacts originated from the raw material acquisition, followed by the fishmeal and fish oil processing, and the usage of cleaning agents, waste and maintenance. Packaging materials and the backup power (operated on heavy fuel oil) did not appear as hotspots for any of the assessed impact categories. However, packaging provides a significant part of the total environmental burden when producing canned mackerel and herring (Thrane et al., 2009). The hotspot for global warming impact lies in the raw material acquisition, causing 69% of the total global warming impacts across the assessed life cycle stage (Table 9). For terrestrial acidification, ozone formation, and fine particulate matter formation, more than 98% of each of the impact categories came from the raw material acquisition (Table 9). This was not surprising since the assessed fishing vessels operate entirely on heavy fuel oil, and uses high quantities of oil lubricant and other fossil-based materials. Moreover, 90% of the fossil resource scarcity originated from the raw material acquisition.

Results from the midpoint evaluation of Scenario 1 (Table 9), where fishmeal and fish oil production entirely operate on heavy fuel oil, most environmental hotspots shifted to the processing life cycle stage. Packaging material and backup power remained negligible (causing less than 2% of the impacts per assessed impact category), and the proportional contribution of cleaning agents, waste and maintenance, became a smaller part of the environmental impact compared to Scenario 0. While water consumption was highest in the processing life cycle stage in Scenario 0, water consumed was the highest in the raw material acquisition in Scenario 1, or 97% of the total impact, due to the different energy sources. Environmental hotspots related to the burning of fossil fuels in Scenario 1 were the highest in the processing, such as terrestrial ecotoxicity (91%) and global warming (68%), of the total impact per impact category.

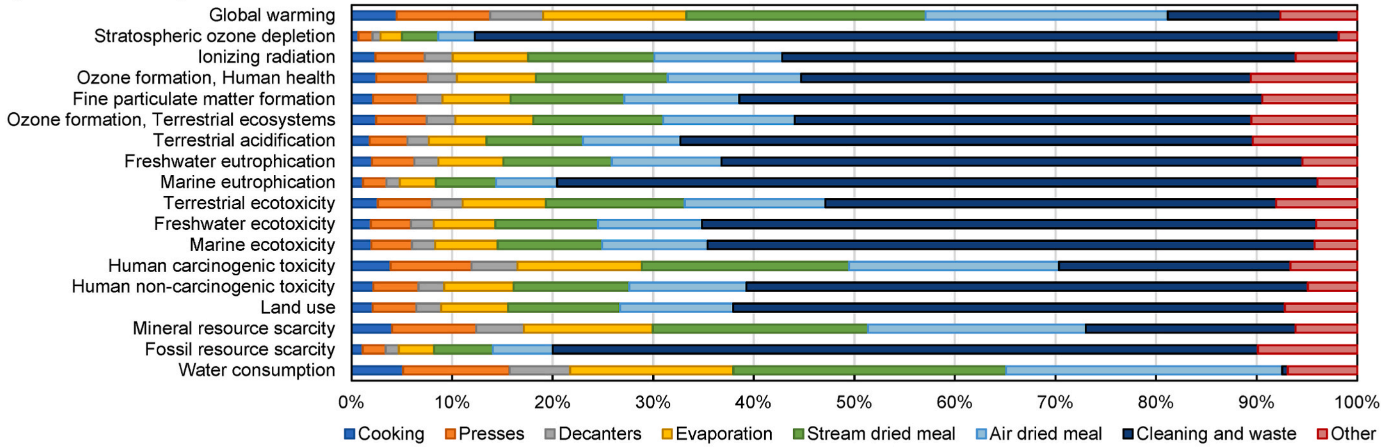
Scenario 2 showed similar trends as Scenario 0 (Table 9), as a high proportion of green energy sources was portrayed in Scenario 2. The division of environmental hotspots across impact categories, between processing, raw material acquisition, and cleaning, waste and maintenance, followed the same trends as in Scenario 0. Packaging and backup power remained close to 0% of the total impacts in most impact categories. Terrestrial acidification, ozone formation, fine particulate matter formation, and water consumption remained highest during the raw material acquisition (>76%), related to the burning of fossil fuels, and remained the same as in Scenario 0 and Scenario 1. Categories as terrestrial ecotoxicity remained highest in processing (71%), which resulted in a similar distribution of environmental hotspots as in Scenario 1.

In all Scenarios, the highest environmental impact of terrestrial ecotoxicity, freshwater and marine eutrophication originated from the cleaning waste and maintenance life cycle stage. Furthermore, the highest impact on ozone formation in terrestrial ecosystems and human health originated from the raw material life cycle stage across all the Scenarios.

3.6. *Identification of other potential optimization steps based on hotspots analysis*

Results from the hotspot analysis indicated where to focus future optimizations of the fishmeal and fish oil production on minimizing its environmental impact. However, the results do not summarize what can be changed to improve the environmental impact in each process. Hence, the sensitivity scenarios will identify those improvement points

a) Scenario 0: Hydropower



b) Scenario 1: Heavy fuel oil

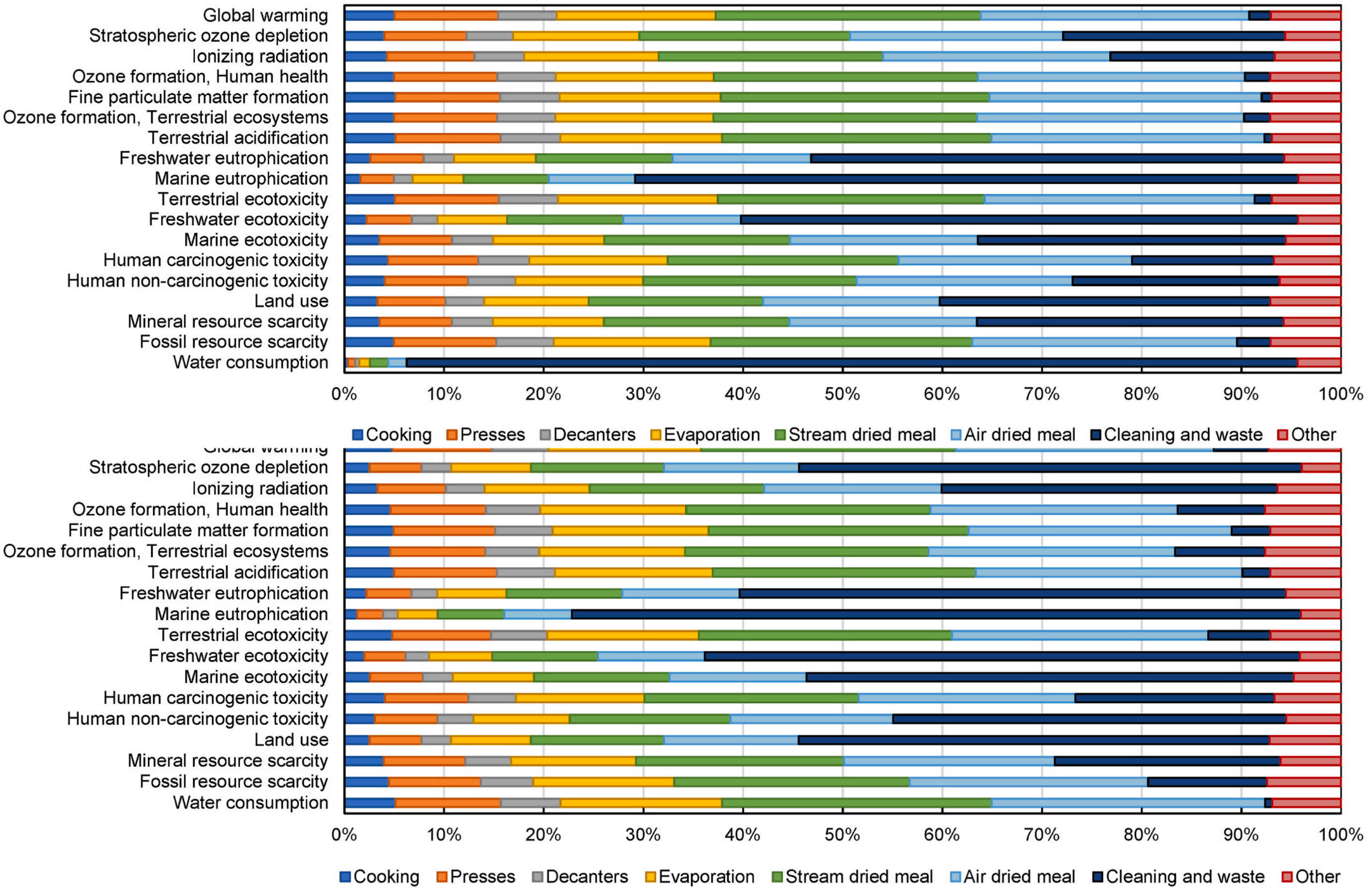


Fig. 4. Midpoint analysis of capelin fishmeal and fish oil production processes operating with 90 °C cooking temperature on different energy sources. Processing steps marked as "Other" summarize centrifuges, packaging material, and backup power.

(see Table 10).

The recommended energy source producing fishmeal and fish oil is hydropower (or other green energy sources), as operating the factory on heavy fuel oil is estimated to have more than double the impact on global warming, stratospheric ozone depletion, ionizing radiation, fine particulate matter formation, terrestrial acidification and human non-carcinogenic toxicity. Furthermore, heavy fuel oil was estimated to be three times higher in fossil resource scarcity and over nine times higher in terrestrial ecotoxicity. Hence, changing the energy source to hydropower would lower the environmental impact significantly. It is also estimated that changing to other more sustainable energy sources, where hydropower is not available, would potentially lower the environmental impacts of fishmeal and fish oil production but requires further investigation.

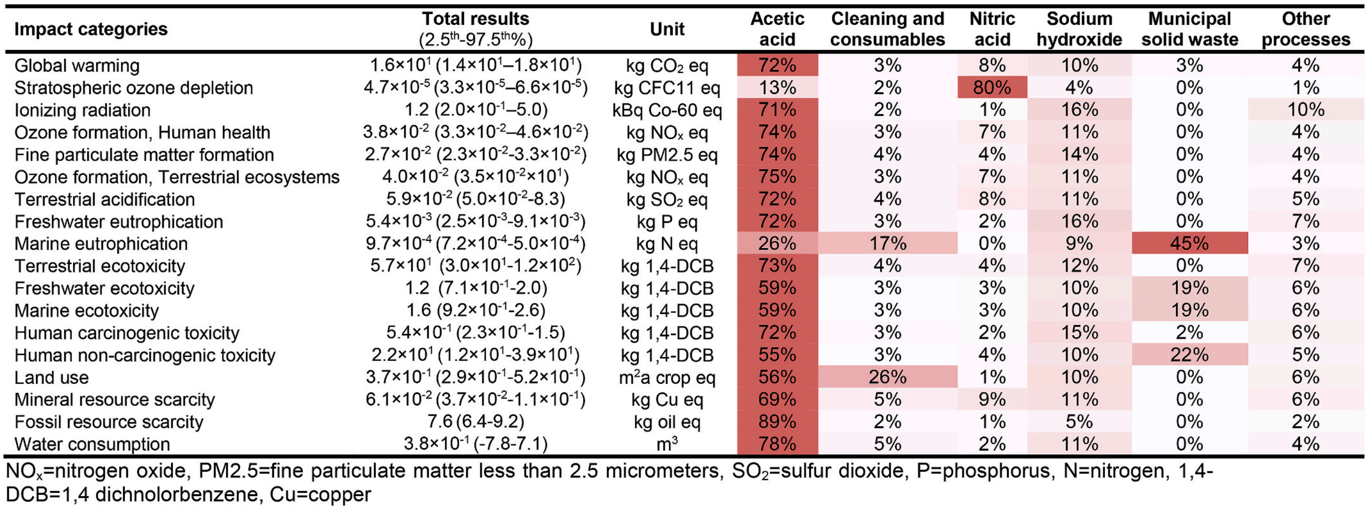
The raw material acquisition turned out to have a high impact on the environmental impact categories and was affected by several factors. Land-based connection to electricity at the harbor has for example become more frequent, which is estimated to save around 300 000 L of oil annually (Morgunbladid, 2021). This indicates that a combination of actions can be taken to decrease the environmental impact of the raw material acquisition. Along with altering the energy source, the fishing gear can affect the environmental impact, where purse seiner resulted in

Table 7
Overall gain of environmental impact categories estimated at 85 °C and 90 °C cooking temperature, respectively. The environmental impact was multiplied by an estimation of annual production of capelin fishmeal (18.5% fishmeal yield) in 2018 in Iceland in each Scenario.

Impact categories	Gain from lowering the cooking temperature from 90 °C to 85 °C			Unit	Annual gain from lowering the cooking temperature from 90 °C to 85 °C based on annual capelin fishmeal production in Iceland (2018		
	Scenario 0	Scenario 1	Scenario 2		Scenario 0	Scenario 1	Scenario 2
Global warming	0.6%	0.6%	0.6%	kg CO_2 eq	194	217	205
Stratospheric ozone depletion	0.1%	0.5%	0.3%	kg CFC11 eq	29	172	107
Ionizing radiation	0.3%	0.5%	0.4%	kBq Co-60 eq	102	183	141
Ozone formation, Human health	0.3%	0.6%	0.6%	kg NO_x eq	107	216	195
Fine particulate matter formation	0.3%	0.6%	0.6%	kg PM2.5 eq	92	220	208
Ozone formation, Terrestrial ecosystems	0.3%	0.6%	0.6%	kg NO_x eq	105	215	195
Terrestrial acidification	0.2%	0.6%	0.6%	kg SO_2 eq	78	220	210
Freshwater eutrophication	0.3%	0.3%	0.3%	kg P eq	88	112	94
Marine eutrophication	0.1%	0.2%	0.2%	kg N eq	49	70	54
Terrestrial ecotoxicity	0.3%	0.6%	0.6%	kg 1,4-DCB	112	218	202
Freshwater ecotoxicity	0.2%	0.3%	0.2%	kg 1,4-DCB	83	95	86
Marine ecotoxicity	0.2%	0.4%	0.3%	kg 1,4-DCB	84	152	109
Human carcinogenic toxicity	0.5%	0.5%	0.5%	kg 1,4-DCB	168	189	173
Human non-carcinogenic toxicity	0.3%	0.5%	0.4%	kg 1,4-DCB	94	174	129
Land use	0.3%	0.4%	0.3%	m^2a crop eq	91	142	108
Mineral resource scarcity	0.5%	0.4%	0.5%	kg Cu eq	174	151	169
Fossil resource scarcity	0.1%	0.6%	0.5%	kg oil eq	48	214	188
Water consumption	0.6%	0.0%	0.6%	m^3	221	15	220

Abbreviations: CO_2 = carbon dioxide, Eq = equivalent, CFC11 = trichlorofluoromethane or freon-11, Co-60 = cobalt isotope ^{60}Co, NO_x = nitrogen oxide, PM2.5 = fine particulate matter less than 2.5 μm, SO_2 = sulfur dioxide, P = phosphorus, N = nitrogen, 1,4-DCB = 1,4 dichnolorbenzene, Cu = copper.

Table 8
Impact categories of the cleaning, waste, and maintenance processing step. Total results and the effect of each component on the impact category are presented. Darker colours represent a higher environmental impact.



Impact categories	Total results (2.5^{th}-97.5^{th}%)	Unit	Acetic acid	Cleaning and consumables	Nitric acid	Sodium hydroxide	Municipal solid waste	Other processes
Global warming	1.6×10^{1} (1.4×10^{1}–1.8×10^{1})	kg CO_2 eq	72%	3%	8%	10%	3%	4%
Stratospheric ozone depletion	4.7×10^{-5} (3.3×10^{-5}–6.6×10^{-5})	kg CFC11 eq	13%	2%	80%	4%	0%	1%
Ionizing radiation	1.2 (2.0×10^{-1}–5.0)	kBq Co-60 eq	71%	2%	1%	16%	0%	10%
Ozone formation, Human health	3.8×10^{-2} (3.3×10^{-2}–4.6×10^{-2})	kg NO_x eq	74%	3%	7%	11%	0%	4%
Fine particulate matter formation	2.7×10^{-2} (2.3×10^{-2}-3.3×10^{-2})	kg PM2.5 eq	74%	4%	4%	14%	0%	4%
Ozone formation, Terrestrial ecosystems	4.0×10^{-2} ($3.5\times10^{-2}\times10^{1}$)	kg NO_x eq	75%	3%	7%	11%	0%	4%
Terrestrial acidification	5.9×10^{-2} (5.0×10^{-2}-8.3)	kg SO_2 eq	72%	4%	8%	11%	0%	5%
Freshwater eutrophication	5.4×10^{-3} (2.5×10^{-3}-9.1×10^{-3})	kg P eq	72%	3%	2%	16%	0%	7%
Marine eutrophication	9.7×10^{-4} (7.2×10^{-4}-5.0×10^{-4})	kg N eq	26%	17%	0%	9%	45%	3%
Terrestrial ecotoxicity	5.7×10^{1} (3.0×10^{1}-1.2×10^{2})	kg 1,4-DCB	73%	4%	4%	12%	0%	7%
Freshwater ecotoxicity	1.2 (7.1×10^{-1}-2.0)	kg 1,4-DCB	59%	3%	3%	10%	19%	6%
Marine ecotoxicity	1.6 (9.2×10^{-1}-2.6)	kg 1,4-DCB	59%	3%	3%	10%	19%	6%
Human carcinogenic toxicity	5.4×10^{-1} (2.3×10^{-1}-1.5)	kg 1,4-DCB	72%	3%	2%	15%	2%	6%
Human non-carcinogenic toxicity	2.2×10^{1} (1.2×10^{1}-3.9×10^{1})	kg 1,4-DCB	55%	3%	4%	10%	22%	5%
Land use	3.7×10^{-1} (2.9×10^{-1}-5.2×10^{-1})	m^2a crop eq	56%	26%	1%	10%	0%	6%
Mineral resource scarcity	6.1×10^{-2} (3.7×10^{-2}-1.1×10^{-1})	kg Cu eq	69%	5%	9%	11%	0%	6%
Fossil resource scarcity	7.6 (6.4-9.2)	kg oil eq	89%	2%	1%	5%	0%	2%
Water consumption	3.8×10^{-1} (-7.8-7.1)	m^3	78%	5%	2%	11%	0%	4%

NO_x=nitrogen oxide, PM2.5=fine particulate matter less than 2.5 micrometers, SO_2=sulfur dioxide, P=phosphorus, N=nitrogen, 1,4-DCB=1,4 dichnolorbenzene, Cu=copper

a lower environmental impact compared to trawling due to lesser fuel usage.

In the production process, the drying and evaporation steps together accounted for 48–54% of the total environmental impact (not depending on the energy source) of global warming. Hence, optimizing these steps might result in a great environmental gain despite the energy source. A small change as lowering the cooking temperature by 5 °C resulted in a visible environmental gain in the production process, even though cooking accounted for <5% in the impact categories. The optimization of drying and evaporation steps will hence be of great beneficial environmental impact. As thermal decrease has resulted in higher quality fishmeal (Hilmarsdottir et al., 2020), optimized drying techniques could lead to higher quality fishmeal.

During the production process, cleaning agents are used excessively, and not necessarily with any restrictions. There are no suggested nor standardized amounts for the usage of cleaning agents. Exchanging cleaning agents with environmentally friendly cleaning agents would positively influence the environment.

4. Conclusions

The current work identified the environmental impacts of producing fishmeal and fish oil and suggested possible solutions that entail changing the energy source in the raw material acquisition.

Although the raw material acquisition resulted as the highest environmental contributor when using green energy sources, the fishmeal and fish oil accounted for the highest environmental impact using fossil fuel-based energy. It is clear that drying and evaporation contributed to a large part of the fishmeal and fish oil processing production, and with minor changes, such as changing the cooking temperature during the production, positive impacts on the environment may be achieved. Lowering the cooking temperature from 90 °C to 85 °C impacted all

Table 9

Hotspot analysis of the Scenarios during capelin fishmeal and fish oil production at 90 °C cooking temperature. Darker color indicates a higher environmental impact. Backup power was 1% in terrestrial ecotoxicity in Scenario 0, but 0% in other categories in all Scenarios.

***Scenario 0*: Hydropower**	**Total results** (2.5th-97.5th%)	**Unit**	**Raw material**	**Processing**	**Packaging**	**Cleaning, waste and maintenance**
Global warming	4.5×10^{2} (4.3×10^{2}-4.8×10^{2})	kg CO$_2$ eq	70%	26%	0%	3%
Stratospheric ozone depletion	1.5×10^{-4} (1.1×10^{-4}-2.2×10^{-4})	kg CFC11 eq	64%	5%	0%	31%
Ionizing radiation	5.1 (1.7-1.5×10^{1})	kBq Co-60 eq	57%	19%	1%	23%
Ozone formation, Human health	7.1 (4.8-1.0×10^{1})	kg NOx eq	99%	1%	0%	1%
Fine particulate matter formation	2.3 (2.0-2.7)	kg PM2.5 eq	98%	1%	0%	1%
Ozone formation, Terrestrial ecosystems	7.2 (4.8-1.0×10^{1})	kg NO$_x$ eq	99%	1%	0%	1%
Terrestrial acidification	7.3 (6.4-8.4)	kg SO$_2$ eq	99%	0%	0%	1%
Freshwater eutrophication	1.3×10^{-2}(6.1×10^{-3}-2.8×10^{-2})	kg P eq	30%	27%	2%	41%
Marine eutrophication	1.6×10^{-3}(1.3×10^{-3}-2.1×10^{-3})	kg N eq	22%	16%	2%	60%
Terrestrial ecotoxicity	4.0×10^{2}(2.5×10^{2}-6.7×10^{2})	kg 1,4-DCB	69%	15%	0%	14%
Freshwater ecotoxicity	2.6 (1.8-4.0)	kg 1,4-DCB	27%	26%	1%	46%
Marine ecotoxicity	3.8 (2.6-5.5)	kg 1,4-DCB	33%	25%	1%	41%
Human carcinogenic toxicity	3.6 (1.9-7.7)	kg 1,4-DCB	38%	46%	1%	15%
Human non-carcinogenic toxicity	5.8×10^{1}(3.8×10^{1}-9.4×10^{1})	kg 1,4-DCB	34%	27%	1%	38%
Land use	1.2 (9.2×10^{-1}-1.6)	m^{2}a crop eq	44%	22%	2%	31%
Mineral resource scarcity	3.8×10^{-1} (2.4×10^{-1}-6.3×10^{-1})	kg Cu eq	27%	56%	0%	16%
Fossil resource scarcity	1.1×10^{2} (9.8×10^{1}-1.3×10^{2})	kg oil eq	90%	2%	0%	7%
Water consumption	8.1×10^{1}(-8.4×10^{3}-6.8×10^{3})	m^3	18%	81%	0%	0%
***Scenario 1*: Heavy fuel oil**						
Global warming	1.0×10^{3} (9.7×10^{2}-1.1×10^{3})	kg CO$_2$ eq	31%	67%	0%	1%
Stratospheric ozone depletion	3.0×10^{-4} (1.8×10^{-4}-5.2×10^{-4})	kg CFC11 eq	32%	52%	0%	15%
Ionizing radiation	9.6×10^{1} (3.6-2.3×10^{1})	kBq Co-60 eq	30%	57%	1%	11%
Ozone formation, Human health	8.5 (5.9-1.2×10^{1})	kg NOx eq	83%	16%	0%	0%
Fine particulate matter formation	4.8 (2.7-1.4×10^{1})	kg PM2.5 eq	47%	53%	0%	1%
Ozone formation, Terrestrial ecosystems	8.5 (6.0-1.2×10^{1})	kg NO$_x$ eq	83%	17%	0%	0%
Terrestrial acidification	1.5×10^{1} (8.0-4.6×10^{1})	kg SO$_2$ eq	48%	51%	0%	0%
Freshwater eutrophication	1.5×10^{-2} (6.5×10^{-3}-3.4×10^{-2})	kg P eq	26%	36%	2%	34%
Marine eutrophication	1.8×10^{-3} (1.4×10^{-3}-2.4×10^{-3})	kg N eq	20%	24%	2%	52%
Terrestrial ecotoxicity	3.4×10^{3} (2.1×10^{3}-5.6×10^{3})	kg 1,4-DCB	8%	90%	0%	1%
Freshwater ecotoxicity	2.8 (1.9-4.2)	kg 1,4-DCB	25%	31%	1%	41%
Marine ecotoxicity	6.1 (4.4-8.5)	kg 1,4-DCB	20%	53%	1%	24%
Human carcinogenic toxicity	5.0 (3.2-8.8)	kg 1,4-DCB	28%	61%	0%	10%
Human non-carcinogenic toxicity	1.2×10^{2} (7.7×10^{1}-2.0×10^{2})	kg 1,4-DCB	16%	65%	0%	17%
Land use	1.6 (1.1-2.6)	m^{2}a crop eq	33%	42%	2%	22%
Mineral resource scarcity	2.9×10^{-1} (1.8×10^{-1}-4.8×10^{-1})	kg Cu eq	36%	43%	1%	20%
Fossil resource scarcity	3.2×10^{2} (2.4×10^{2}-4.2×10^{2})	kg oil eq	32%	65%	0%	2%
Water consumption	1.5×10^{1}(-1.0×10^{1}-3.7×10^{1})	m^3	97%	0%	0%	2%
***Scenario 2*: Composition of hydropower (75.4%) and heavy fuel oil (24.6%)**						
Global warming	5.9×10^{2} (5.7×10^{2}-6.2×10^{2})	kg CO$_2$ eq	54%	43%	0%	3%
Stratospheric ozone depletion	1.9×10^{-4} (1.3×10^{-4}-3.0×10^{-4})	kg CFC11 eq	51%	23%	0%	25%
Ionizing radiation	6.2 (2.3-1.7×10^{1})	kBq Co-60 eq	47%	34%	1%	19%
Ozone formation, Human health	7.5 (5.2-1.1×10^{1})	kg NOx eq	94%	5%	0%	1%
Fine particulate matter formation	2.9 (2.3-5.0)	kg PM2.5 eq	77%	22%	0%	1%
Ozone formation, Terrestrial ecosystems	7.5 (5.2-1.1×10^{1})	kg NO$_x$ eq	94%	5%	0%	1%
Terrestrial acidification	9.1 (7.0-1.6×10^{1})	kg SO$_2$ eq	78%	21%	0%	1%
Freshwater eutrophication	1.4×10^{-2} (6.1×10^{-3}-2.9×10^{-2})	kg P eq	29%	29%	2%	40%
Marine eutrophication	1.7×10^{-3} (1.3×10^{-3}-2.2×10^{-3})	kg N eq	22%	18%	2%	58%
Terrestrial ecotoxicity	1.1×10^{3} (7.7×10^{2}-1.7×10^{3})	kg 1,4-DCB	24%	70%	0%	5%
Freshwater ecotoxicity	2.7 (1.8-3.9)	kg 1,4-DCB	26%	28%	1%	45%
Marine ecotoxicity	4.3 (3.2-6.1)	kg 1,4-DCB	28%	35%	1%	36%
Human carcinogenic toxicity	4.0 (2.3-7.3)	kg 1,4-DCB	35%	51%	1%	14%
Human non-carcinogenic toxicity	7.4×10^{1} (5.1×10^{1}-1.1×10^{2})	kg 1,4-DCB	27%	42%	1%	30%
Land use	1.3 (1.0-1.8)	m^{2}a crop eq	41%	28%	2%	29%
Mineral resource scarcity	3.6×10^{-1} (2.3×10^{-1}-5.6×10^{-1})	kg Cu eq	29%	54%	1%	17%
Fossil resource scarcity	1.6×10^{2} (1.4×10^{2}-2.0×10^{2})	kg oil eq	63%	32%	0%	5%
Water consumption	6.5×10^{1} (-6.6×10^{3}-5.1×10^{3})	m^3	23%	76%	0%	1%

Abbreviations: CO$_2$=carbon dioxide, Eq=equivalent, CFC11=trichlorofluoromethane or freon-11, Co-60=cobalt isotope ^{60}Co, NO$_x$=nitrogen oxide, PM2.5=fine particulate matter less than 2.5 micrometers, SO$_2$=sulfur dioxide, P=phosphorus, N=nitrogen, 1,4-DCB=1,4 dichnolorbenzene, Cu=copper

Table 10
Optimization potential from the hotspot analysis, based on sensitivity scenarios.

Sensitivity scenario	Scenario description
Raw material acquisition	• Purse seiner resulted in lower energy usage compared to trawl • Changing energy source on the vessels is proposed
The fishmeal and fish oil processing	• A green energy source is proposed • Optimizing the drying and evaporation steps • Exchange cleaning agents for eco-friendly cleaning agents

environmental categories beneficially, although being relatively small gain throughout both the raw material acquisition and the fishmeal and fish oil processing. Drying, evaporating and cleaning resulted in the highest contribution to the environmental impact during the processing. Hence, optimizing the drying and separation techniques might significantly lower the environmental impacts. Limiting the use of cleaning agents or exchanging them for eco-friendly chemicals also had positive effects on the environmental impact. As the fishmeal and fish oil industry moves towards higher sustainability and higher use of green energy in the future, applying the LCA methodology is highly recommended to estimate the effects of the life cycle changes beforehand to contribute positively towards a cleaner production.

Recommended for future research is to investigate alternative energy sources in the raw material acquisition and to change the setup of the traditional fishmeal and fish oil processing to investigate the environmental impact. Optimizing the drying steps and limiting the cleaning agents could not only benefit the environment but perhaps produce a higher quality product.

CRediT authorship contribution statement

Gudrun Svana Hilmarsdóttir: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Ólafur Ögmundarson:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision. **Sigurjón Arason:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **María Gudjónsdóttir:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

System boundary

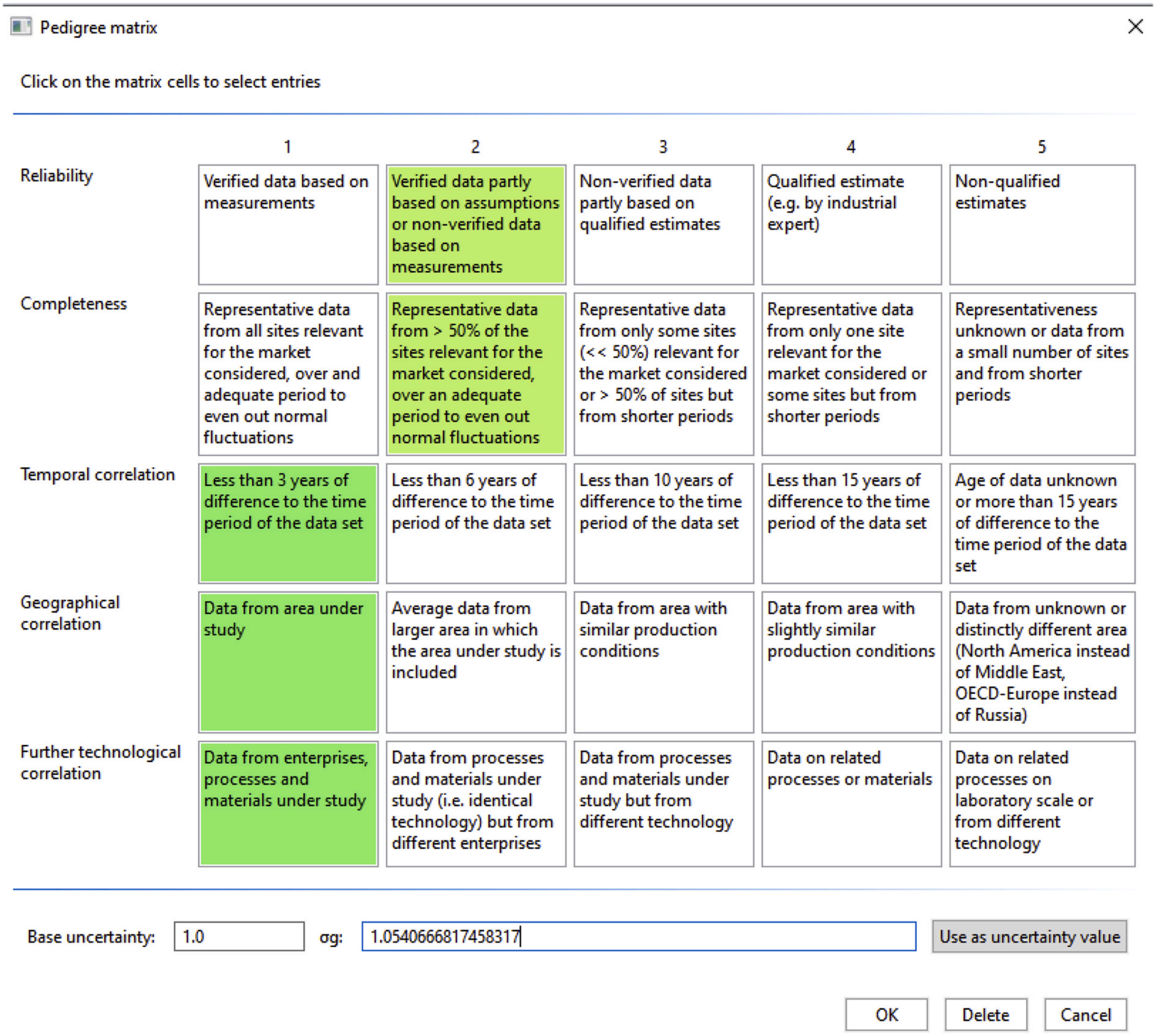
Raw material within the system boundaries per functional unit can be seen in Table A.1.

Table A.1
Raw materials inside the system boundaries per functional unit.

Impact category	Total	Unit	Diesel	Hydraulic fracturing fluid	Lubricating oil	Nylon
Global warming	3.2E+02	kg CO_2 eq	3.2E+02	2.1E-03	5.4E-01	1.6
Stratospheric ozone depletion	9.5E-05	kg CFC11 eq	8.0E-05	1.3E-09	4.9E-07	1.5E-05
Ionizing radiation	2.9	kBq Co-60 eq	2.8	5.3E-05	6.7E-02	3.7E-04
Ozone formation, Human health	7.0	kg NO_x eq	7.0	8.4E-06	3.2E-03	3.3E-03
Fine particulate matter formation	2.3	kg PM2.5 eq	2.2	3.8E-06	1.0E-03	1.3E-03
Ozone formation, Terrestrial ecosystems	7.1	kg NO_x eq	7.1	8.7E-06	4.3E-03	3.4E-03
Terrestrial acidification	7.2	kg SO_2 eq	7.1	9.2E-06	2.8E-03	3.9E-03
Freshwater eutrophication	4.0E-03	kg P eq	3.8E-03	4.8E-07	1.8E-04	3.5E-05
Marine eutrophication	3.6E-04	kg N eq	3.0E-04	8.4E-08	1.2E-05	5.1E-05
Terrestrial ecotoxicity	2.8E+02	kg 1,4-DCB	2.7E+02	1.1E-02	2.7	2.1E-01
Freshwater ecotoxicity	7.0E-01	kg 1,4-DCB	6.6E-01	7.9E-05	3.8E-02	3.8E-03
Marine ecotoxicity	1.2	kg 1,4-DCB	1.2	1.1E-04	5.0E-02	5.3E-03
Human carcinogenic toxicity	1.4	kg 1,4-DCB	1.3	5.9E-05	2.0E-02	2.5E-02
Human non-carcinogenic toxicity	2.0E+01	kg 1,4-DCB	1.9E+01	1.8E-03	6.7E-01	8.1E-02
Land use	5.3E-01	m^2a crop eq	5.2E-01	3.8E-04	1.3E-02	3.7E-04
Mineral resource scarcity	1.0E-01	kg Cu eq	9.9E-02	9.2E-06	4.8E-03	1.1E-04
Fossil resource scarcity	1.0E+02	kg oil eq	1.0E+02	7.2E-04	6.0E-01	4.0E-01
Water consumption	1.5E+01	m^3	1.0E-01	3.2E-05	5.2E-03	1.1E-02

Uncertainty

Uncertainty for acetic acid had to be added manually in the pedigree matrix. To calculate the uncertainty with Monte Carlo analysis, each parameter value must be covered and documented as a statistical parameter (Hauschild et al., 2017). Fig. A.1 demonstrates how the uncertainty value was obtained and how the reliability, completeness, temporal- and geographical- and further technological correlation was estimated.



Pedigree matrix

Click on the matrix cells to select entries

	1	2	3	4	5
Reliability	Verified data based on measurements	[✓ Verified data partly based on assumptions or non-verified data based on measurements]	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	[✓ Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations]	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	[✓ Less than 3 years of difference to the time period of the data set]	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set
Geographical correlation	[✓ Data from area under study]	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	[✓ Data from enterprises, processes and materials under study]	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Base uncertainty: 1.0

σg: 1.0540666817458317

Figure A.1. Uncertainty for acetic acid manually added in SimaPro

Raw material acquisition

The documented annual energy usage from fishmeal and fish oil producers for the years 2017–2019 are summarised in Table A.2, where the division between oil and electricity was calculated for Scenario 2, or 75.4% hydropower and 24.6% heavy fuel oil.

Table A.2
Energy use from different energy resources for the fishmeal and fish oil production in Iceland in 2017–2019 (FIF, 2019).

Energy use from different energy resources for fishmeal and fish oil production in 2017–2019						
Year	Oil		Electricity		Raw material (tonne)	Energy ratio (oil)
	Liters	liters/tonne RM	kWh	kWh/tonne		
2017	8.0E+06	13.7	2.3E+08	401.2	5.8E+05	0.3
2018	7.7E+06	11.7	2.4E+08	368.9	6.6E+05	0.2
2019	3.4E+06	8.3	1.7E+08	427.4	4.1E+05	0.2

The raw material acquisition was estimated from seven fishing trips from one fishing vessel during the capelin season in 2018. Table A.3 demonstrates the fuel usage and time at each trip in 2018 and compared the energy use when using trawl to purse seiner.

Table A.3
Fuel usage and time during raw material acquisition was divided into sailing towards catching ground, catching and superchilling, and sailing towards shore.

Dates from capelin catching from one vessel		Fuel usage			Time		
		Sailing towards catching ground	Catching and superchilling	Sailing towards shore	Sailing towards catching ground	Catching and superchilling	Sailing towards shore
Trip nr. 1)	6.1.-10.1.	34%	30%	35%	19%	70%	11%
Trip nr. 2)	12.1.-16.1.	28%	27%	46%	14%	74%	12%
Trip nr. 3)	17.1.-21.1.	28%	31%	42%	30%	62%	8%
Trip nr. 4)	21.1.-23.1.	30%	38%	32%	15%	72%	14%
Average fuel and time with trawl		30 ± 3%	**31 ± 4%**	**39 ± 6%**	19 ± 7%	69 ± 5%	11 ± 2%
Trip nr. 5)	27.2.-2.3.	45%	14%	42%	23%	47%	30%
Trip nr. 6)	5.3.-9.3.	33%	25%	41%	38%	59%	3%
Trip nr. 7)	10.3.-14.3.	14%	12%	73%	15%	73%	12%
Average fuel and time with purse seiner		31 ± 15%	**17 ± 7%**	**52 ± 18%**	25 ± 11%	60 ± 13%	15 ± 14%
Overal average fuel and time (trip 1–7)		30 ± 9%	25 ± 9%	44 ± 13%	22 ± 9%	65 ± 10%	13 ± 8%

Values on energy consumption during air-drying in the fishmeal and fish oil production. Calculations are based on values obtained from a Mollier diagram (Table A.4).

Table A.4
Calculations of the energy estimations for air-drying fishmeal and fish oil from a Mollier diagram.

	T [°C]	RH [%]	x [kg water/kg air]	i [kJ/kg air]
1	5	80	0.004	15
2	450	1	0.004	430
3	65	100	0.145	430

Midpoint analysis of the fishmeal and fish oil processing

Table A.5 demonstrates calculated values during a full capacity of the fishmeal and fish oil production plant, with a different cooking temperature in the cookers (85 °C and 90 °C). Values were calculated from heating the raw material from 50 °C to 85 °C or 90 °C with different raw materials. The mass balances during production can be seen in Fig. 3.

Table A.5
Power usage (kWh) during full operational capacity at each processing steps during fishmeal and fish oil production at 85 °C and 90 °C cooking temperature.

kWh during full capacity	Capelin		Mackerel/herring blend		Blue Whiting	
Processing steps	90 °C	85 °C	90 °C	85 °C	90 °C	85 °C
Cookers	241	211	301	263	267	234
Presses	254		254		254	
Decanters	144		144		144	
Centrifuges 1	38		38		38	
Evaporator	765		916		782	
Centrifuges 2	51		51		51	
Steam dryer	1277		645		1175	
Air dryer	1293		1331		1090	
Centrifuges 3	76		76		76	

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