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Life Cycle Inventories of marine ingredients

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A B S T R A C T

Marine ingredients are still regarded as a vital constituent of aquaculture and other livestock feeds. Despite numerous publications that have discussed the sustainability issues, there are few sources that provide detailed information that allow for quantification of marine ingredient environmental impact. A Life Cycle Inventory was compiled from many available literature sources that will allow for Life Cycle Assessments (LCAs) of marine ingredients using standard methodologies. While this inventory is the most complete to date, there are still important data gaps that the industry should endeavour to fill. Demonstration of the inventory using an economically allocated LCA showed that marine ingredients are very variable in their impact between and even within species, mostly depending on the fuel intensity of the fishery from which they are sourced. Marine ingredients were typically lower in environmental footprint compared to terrestrial ingredients, although LCAs do not take into account the stock status of fisheries, which must be considered separately.

1. Introduction

Marine ingredients (MIs) are important within aquatic and terrestrial animal diets to provide macro- and micro-nutrients as well as important organoleptic properties that aid the digestibility and performance of formulated feed. MIs are most commonly meals and oils that are rendered from small pelagic fish and the by-products of fish and seafood processing. MIs were a central foundation of diets at the beginnings of Atlantic salmon culture, providing good quality nutrition to the fish aligned with dietary requirements. MIs were also highly favoured because they resulted in the final product being high in omega-3 fatty acids, that are highly beneficial in human diets (Sprague et al., 2016). They are also considered important at various life stages, especially for juveniles of salmonids and other aquaculture species, and in chicken and pig diets for improving survival at critical life stages such as weaning (Kim and Easter, 2001; Karimi, 2006; Burr et al., 2012).

MIs are valued for their amino-acid profiles (Hemre et al., 2016), but the specific requirements and ratios depend on the species and life cycle of the animals being fed and is complicated further in fish by the requirements for gluconeogenesis, i.e. the utilisation of protein as an energy source (Suarez and Mommsen, 1987). To reduce protein being utilised as an energy source, the amino acid profile of the diet can be matched to that in the carcass of the animal being cultured using the "ideal protein" concept (Ikoma et al., 2003; Furuya et al., 2004), although the exact profile may vary due to amino acid digestibility and specific amino acid preference for gluconeogenesis (Suarez and Mommsen, 1987). The amino acid profile of soybean, the most substituted vegetable protein, is also different from fishmeal and especially limited in lysine and methionine which are consequently often supplemented individually in crystalline form. Such a strategy however has drawbacks, in that supplements are both more subject to leaching in water (Furuya et al., 2004) and less digestible than protein-bound amino acids (Cowey and Walton, 1988; Sveier et al., 2001). Some commercially available crystalline amino acids can be produced organically (FAO, 2003), which produces only bioavailable L-enantiomers (e.g. L-lysine), but some must be produced by chemical synthesis which contains both D and L enantiomers (e.g. D/L methionine) (Grishin et al., 2019). However both processes can be energy intensive (Marinussen and Kool, 2010). Additionally, D-enantiomers can have adverse effects on nutrition and hence feed efficiency (Sveier et al., 2001; Grishin et al., 2019) and is sometimes separated out or converted, which adds to the cost and energy requirements but can rarely be done with 100% efficiency (Grishin et al., 2019).

Fishmeal is also high in levels of key micronutrients such as readily available B complex vitamins, phosphorus, magnesium, potassium and selenium, and it has been shown that as MIs are replaced by alternatives, health problems associated with micronutrient deficiencies can be common (Olsvik et al., 2013; Hemre et al., 2016). B-vitamins (Hemre

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et al., 2016) and phosphorous (Li et al., 2019), are cofactors associated with metabolism of proteins, carbohydrates and lipids. However, phosphorous in plant-based ingredients often occurs in the form of phytate which cannot be readily utilised by fish, leading to impaired performance (Furuya et al., 2004; Li et al., 2019) and a requirement for vitamin and mineral supplements (Olsvik et al., 2013). Several authors have made the link between sub-optimal micronutrient levels and lipid deposition around the organs of Atlantic salmon as reported by Hemre et al. (2016). Hence, formulators add vitamin and mineral premixes to their diets to compensate for deficiencies due to MI substitution (Olsvik et al., 2013). However, the situation regarding micronutrient deficiencies is complex and may vary according to each formulation as reviewed by Prabhu et al. (2016).

The environmental impacts from aquaculture can be considered as local emissions at the farm site or global impacts that occur throughout the value/supply chain. Local impacts include specific aspects such as benthic organic and other nutrient enrichment, disease transfer to wild populations such as sea lice and genetic impacts from escapees (Torrissen et al., 2011). Global impacts are primarily a direct consequence of the diet formulation and are usually accounted for using the Life Cycle Assessment approach (LCA). LCA is an environmental impact accounting method which sums emissions of a production chain from "cradle-to-grave". LCA is favoured as a method of benchmarking the impact of products because it avoids problem shifting, e.g., a potential change in diet that has no impact on the farm but results in increased carbon footprints or eutrophication elsewhere. The methodology is standardised by the International Standards Organisation (ISO, 2006a, 2006b) and further strengthened by EU Product Environmental Footprint Category Rules (PEFCR) (EC, 2021). Several LCAs of Atlantic salmon farming have been produced and all of them have demonstrated the provision of feed to be responsible for over 90% of all impacts, apart from eutrophication at the aquaculture facility (e.g., Pelletier et al. (2009), Newton and Little (2018)).

The impact of aquaculture on fisheries underpinning the MI industry has particularly been linked to the growth in carnivorous aquaculture species such as salmonids, although the dominant absolute production of a range of omnivorous species (with lower MI inclusions within diet formulations) uses a large proportion of global MI supplies (Tacon and Metian, 2015; Newton et al., 2021). The use of MIs had been well established in livestock nutrition for several decades and contrary to popular perception, MI production was already at its limit well before the rapid growth in salmonid aquaculture took up an ever-increasing share of that finite supply (Naylor et al., 2009; Shepherd and Jackson, 2013). However, global aquaculture now consumes around 69% of fishmeal and 75% of fish oil supplies (Naylor et al., 2021), although these levels fluctuate because of volatile fishery catches of the main reduction fishery species (Fig. 1), such as anchovy (*Engraulis ringens*). The consequent pressures on MI supplies led to increased costs and, coupled with negative media and public perception, resulted in a continual decrease in the percentage inclusion of MIs in Atlantic salmon diets as detailed in (Aas et al., 2022). However, the plant-based replacements for MIs such as soybean protein concentrate, wheat and corn (maize) gluten, pea protein concentrate, rapeseed and palm oil, also have their own environmental impact issues (Malcorps et al., 2019). Soybean and palm oil are both often associated with unsustainable deforestation (Schmidt, 2010; da Costa et al., 2017) while wheat or corn gluten, rapeseed oil, protein concentrates and many novel ingredients are energy intensive to produce leading to high greenhouse gas emissions (Newton and Little, 2018; Maiolo et al., 2020). Therefore, there are important environmental trade-offs between MIs and their replacements that must be considered using LCA and holistic sustainability assessments.

Many aquaculture stakeholders are reluctant to further reduce inclusions of MIs because of impacts on fish health, welfare and performance in the farmed environment described above and because of a fall in the content of omega-3 fatty acids within salmon products (Sprague et al., 2016). A range of novel feed ingredients have emerged to try to bridge the supply gap but none have been widely adopted at commercial scales, suffering from cost, scalability issues (Pelletier et al., 2018) and questionable sustainability credentials (Hua et al., 2019; Smetana et al., 2019; Maiolo et al., 2020). Fig. 1 presents fishery data, not quantities of global MI supply. Although the fishery supply has reduced gradually since the 1990s, a decline in availability of MI has been offset by greater contribution from the by-products of seafood processing, which now represent around a third of MI supply (Jackson and Newton, 2016) (Fig. 2). However, the potential for increasing that supply is considered substantial if logistical and cost barriers to by-product valorisation could be overcome and has emerged as central to circular economy initiatives aiming to reduce waste and provide a much-needed increase in valuable MI supplies (Stevens et al., 2018; Hua et al., 2019; Malcorps et al., 2021; Regueiro et al., 2021). An estimate of available raw material from processing by-products and potential increase in MIs was provided by Jackson and Newton (2016).

According to ISO (2006a, 2006b), Life Cycle Assessment studies should follow a set procedure including "Goal and Scope", "Inventory Analysis", "Impact Assessment" and "Interpretation". The Goal and Scope lays out the boundaries of the study, the audience and important methodological decisions such as allocation and functional unit. Since this paper is a Life Cycle Inventory intended as a data source for other practitioners, many of the methodological decisions remain open

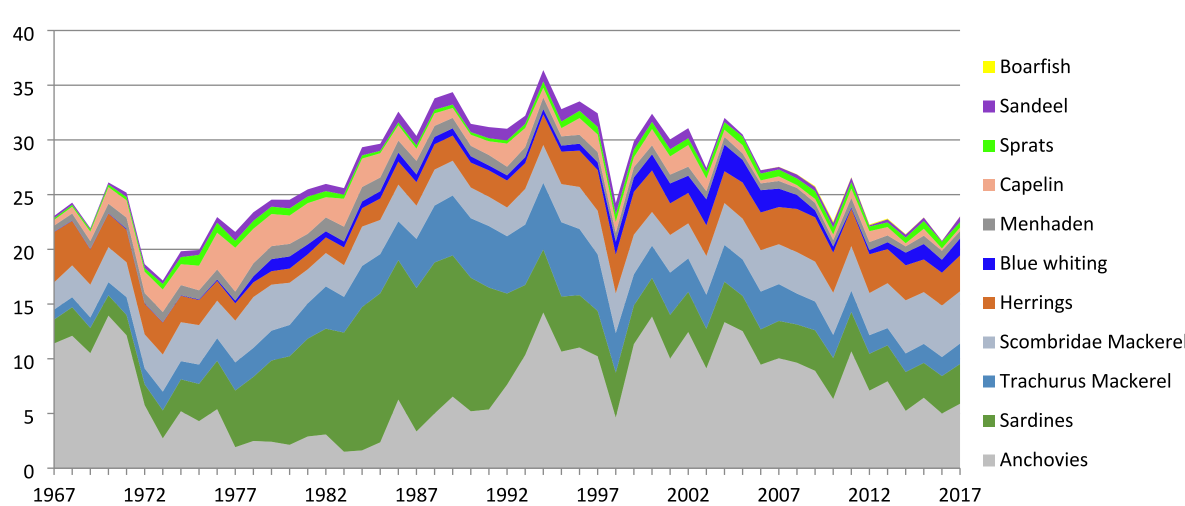

Fig. 1. Global catches (million tonnes) of most important fish species for reduction into MIs 1967–2017 (FAO, 2019).

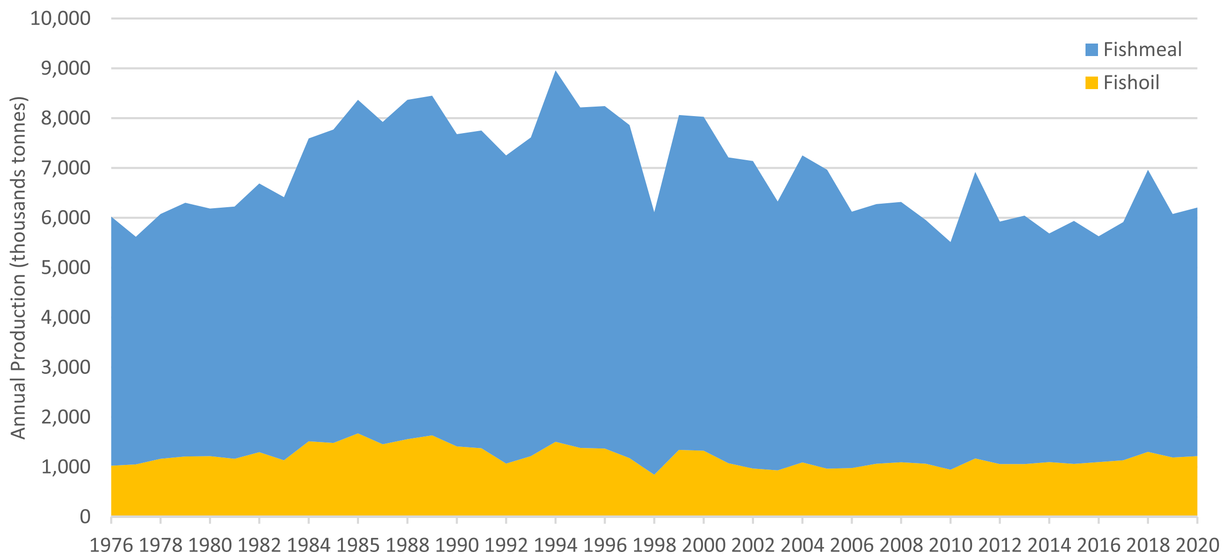

Fig. 2. Global fishmeal and fish oil production from 1976 to 2020 (Data supplied by the Marine Ingredients Organisation, IFFO).

(including allocation) because provisions are made to allow for a number of methodological choices depending on the objectives of subsequent studies. However, we have chosen to validate the inventory within a short Impact Assessment section with some subsequent interpretation within the discussion. Despite the importance of MIs in aquafeeds and other formulated diets, there is little Life Cycle Inventory (LCI) information available that could be used for constructing LCA models. While Cashion et al. (2017) provides a comprehensive list of important MI species with reduction yields and fuel intensity, it is limited in scope and with little transparency on how the data were derived, with most only applicable to Norwegian fisheries. In addition, only mass allocation of impacts between co-products (Svanes et al., 2011a) has been presented which does not meet the necessary requirements for the EU PEFCR on feed ingredients which requires economic allocation to be applied (EC, 2018).

In this article we seek to build on the data provided by Cashion et al. (2017) by a synthesis of published fisheries and rendering LCI data to provide full LCI data sets that can be used to model MIs by LCA, either by mass or economic allocation, meeting the requirements of PEFCR and providing complete transparency on how the inventory data was derived. The Life Cycle Impact Assessments (LCIAs) of selected MIs relevant to salmon aquaculture are provided, calculated from the LCIs provided within the supplementary information and compared to key alternative plant ingredients taken from LCA data bases.

2. Methods

The library/database of LCI data for the MIs were built from an extensive analysis of relevant literature complemented with primary data as follows: 1) fisheries data (LCA, environmental impact, and

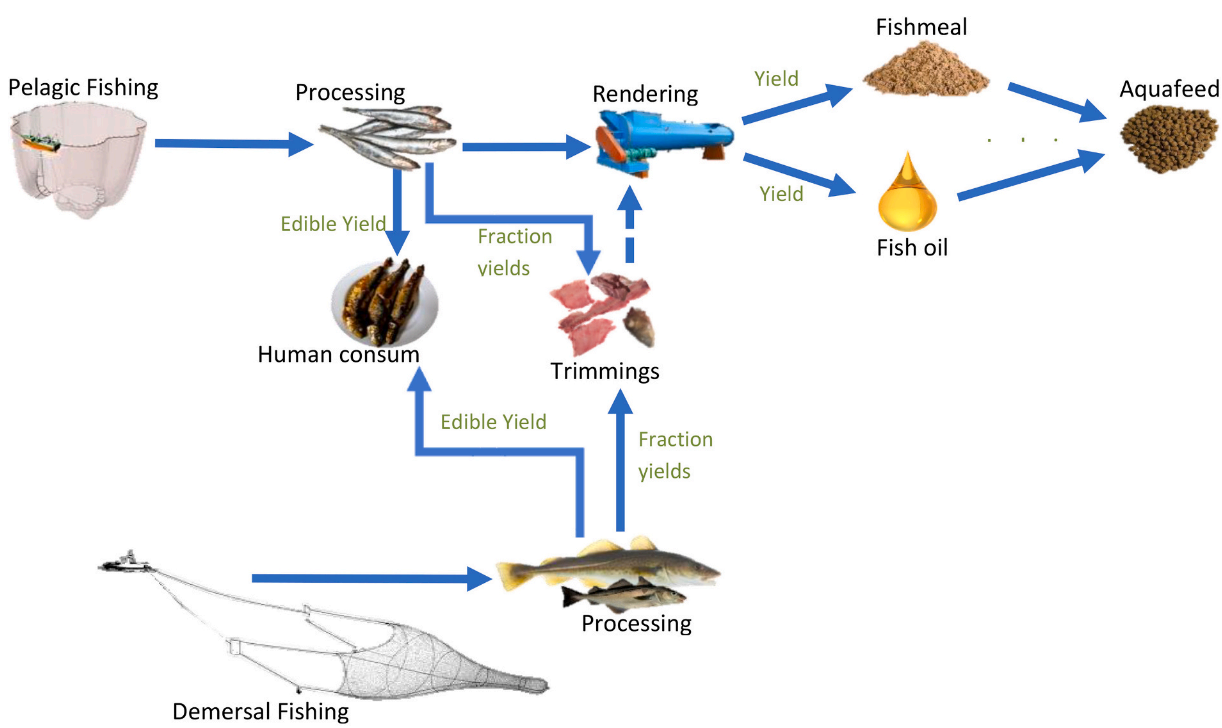

Fig. 3. Schematic overview of the main processes that contribute to marine ingredients Life Cycle Inventories.

energy and fuel consumption studies) related to MI raw materials taken exclusively from literature resources (pelagic purse seiner, mid-water and demersal trawling), 2) processing data from a mixture of primary data collection and literature resources, 3) rendering data sourced from literature sources (Fig. 3). This library was then demonstrated on the basis of economic considerations.

Weighted averages and weighted standard deviations were calculated where several data points were present within single literature sources. In some circumstances several data sources were available for species, which were then "horizontally averaged" (Henriksson et al., 2013) and adjusted according to their representativeness. Uncertainty values were presented as SD95 values which can be inputted directly into standard Simapro LCA software. A representative list of species to be included was informed by a published report by Skretting (2018), and communications with major European aquafeed producers. The inventory does not include MIs from Asian sources, for which the data is scarce and complex, for example, as highlighted by Zhang et al. (2019) on Chinese feed fisheries that consists of over two hundred species from various fishery types including juveniles. The inventory also does not include data on by-catch used in MIs or the increasing range of fish hydrolysates on the market (Chalamaiah et al., 2012; He et al., 2013; Zamora-Sillero et al., 2018) for which LCI data availability is very limited. The full inventory data included in this study can be viewed in the supplementary information with an overview of the data collection and default values presented in the main article.

2.1. Fisheries

Fishery LCI data were only included where it could be directly related to MI production and did not include fisheries targeted solely for human consumption. Similarly, only data that could be attributed to individually defined species were included and some data sources were rejected because the LCI data was not provided, could not be disaggregated to species level or because they were considered unreliable with inputs orders of magnitude higher from similar species. It was assumed that the lifetime construction and maintenance requirements for fishing boats was related to fishing effort rather than volume of catch and therefore the inputs and emissions data extracted from literature were adjusted to fuel intensity. Data were extrapolated from Fréon et al. (2017), Ramos et al. (2011) and Vazquez-Rowe et al. (2010) for purse seiner fisheries and from Fulton (2010), Svanes et al. (2011b), Vazquez-Rowe et al. (2010) and Vázquez-Rowe et al. (2011) for trawlers and horizontally averaged (Henriksson et al., 2013) to provide a default LCI for boat construction and maintenance per 1000 MJ of fuel used. Fuel intensity is considered to be the most important contribution to LCAs of fisheries and is often presented as either litres or kg of diesel per unit catch within the literature. However, fuel use in LCA software is usually determined in MJ of fuel combusted in (boat) engines. In this study a conversion of 0.0234 kg of fuel for every MJ was used with a specific density of 0.84 kg per litre of fuel. Default anti-fouling emissions were also calculated, although this contributes mostly to toxicity and negligibly to the impact categories included in the Supporting Information (SI).

2.2. Processing and rendering

Data on processing were obtained from one major white fish processor in the UK and from the SINTEF (2020) report on Norwegian seafood carbon footprints. Other processing data were found but rejected due to unreliability, as many inputs were several magnitudes different from UK primary and SINTEF (2020) data, which were broadly in agreement. Data on rendering the raw materials into fishmeal and oil was also difficult to obtain. Literature information was available for anchovy and sandeel rendering which was horizontally averaged to provide a default process that was applied to other species. National energy mixes were adjusted to the default processes as appropriate.

2.3. Methodological issues

To provide economic allocation coefficients, long-term price data were used because volatility in prices can lead to skewed outcomes. Especially, real changes in environmental performance over time could be clouded by short-term economic volatility (Svanes et al., 2011a), which is particularly high in fisheries (Vazquez-Rowe et al., 2010). Although, some articles provided their own economic allocation values, they were rejected in preference to long-term average price data from FAO (2020), because it offers greater relative stability over time and for consistency between inventories. More specifically, economic allocation for fisheries was calculated using ten-year price averages derived from commodity trade information available from FAO (2020), over the relevant fisheries for Norwegian, Icelandic and Danish mixed fisheries, Spanish mackerel, sardine and Atlantic horse-mackerel. The proportion that each fishery type contributed to national production was calculated in each case to provide national industry averages. Economic allocation was calculated in the same way throughout the value chain, wherever multi-functional processes occurred: at mixed fisheries, processing into multiple co-products (fillets, other products for human consumption and by-products), and at the MIs rendering stage to produce fishmeal and fish oil. Economic allocation at the processor was according to SINTEF (2020) where main products were priced at US$3.17/kg and by-products at US$0.34/kg (converted from NOK), whereas fishmeal and fish oil prices were derived from ten-year averages from OECD/FAO (2018).

2.4. Impact assessment method

The Life Cycle Inventory Assessments (LCIAs) provided in the supplementary materials have been calculated using CML Baseline methodology and economic allocation presenting Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidation Potential (POP) and Ozone Depletion Potential (ODP), with added impact categories, Biotic Resource Use (BRU) and Fish In Fish Out (FIFO) (Kok et al., 2020) which are especially relevant to MIs. FIFO is presented as the amount of fish required per unit MI production using the allocation procedures outlined above. BRU was calculated according to the formula by Pauly and Christensen (1995) using the trophic level data of species from the Fishbase.org website (accessed 20/4/2021). Blue and Green Consumptive Water Use (CWU) have also been included according to data from Mekonnen and Hoekstra (2011). Effects on Global Warming Potential due to land transformation (Land Use Change - LUC) were minimal for MIs and have not been presented.

3. Results

3.1. Life Cycle Inventory (LCI)

The coverage of the data analysis for fisheries can be seen in Table 1. The Life Cycle Inventories modelled are provided as follows: boat construction and maintenance (Table 2); fishing operations (Table 3); fish processing (Table 5); fish rendering (Table 6). Moreover, these inventories are supplemented by information on antifouling paint composition (Table 4), fishmeal and oil yield (Table 7), BRU values for the main species (Table 8), mass and economic allocation factors applied to Spanish hake fisheries (Table 9).

As shown in the *Data Coverage* column of Table 1, some literature resources provided a full LCI with allocation of impacts between species, but others only provided fuel intensity (litres or kilogrammes of diesel per unit catch) for the species of interest.

Table 2 shows that the default fishing construction and maintenance inputs for trawlers are generally lower than for purse seiners per unit fishing effort (1000 MJ of fuel use). Although trawlers are often larger vessels, the construction and maintenance were standardised to fishing

Table 1
Data coverage for fishing literature resources; PS = purse seine, BT = bottom trawl, MW = Mid-water trawl, LL = long line, RS = ring seine, FI = fuel intensity, OI = operational inputs, BCM = boat construction and maintenance, Pr = processing, R = rendering, M = mass allocation, E = economic allocation, En = Energetic content allocation, SE = system expansion, NA = not applicable (single species fishery), NM = not mentioned.

Source	Species/ raw material used in marine ingredients	Fishing method	Origin	Data coverage	Allocation
Fréon et al. (2014)	Anchoveta	PS	Peru	FI, OI, BCM, R	NA
Almeida et al. (2013)	Sardine	PS	Portugal	FI, OI	M
Ramos et al. (2011)	Atlantic mackerel Sardine	PS	Spain	FI, OI, BCM	SE
Vazquez-Rowe et al. (2010)	Atlantic mackerel Atlantic horse mackerel Blue whiting Sardine	PS, BT	Spain	FI, OI, BCM	M, E
Vázquez-Rowe et al. (2011)	Atlantic mackerel Atlantic horse-mackerel Blue whiting	PS	Spain	FI, OI, BCM	M
Thrane (2004)	Atlantic herring Atlantic mackerel Sandeel Mixed white fish	PS, BT	Denmark	FI, OI	M, E, SE
SINTEF (2020)	Atlantic herring Atlantic mackerel Mixed white fish	PS, BT	Norway	FI, Pr	M
Svanes et al. (2011b)	Mixed white fish	LL	Norway	FI, OI, BCM, Pr	M, E
Fulton (2010)	Mixed white fish	LL	Iceland	FI, OI, BCM	M
Das and Edwin (2016)*	Indian Oil Sardine	RS	India	FI, OI, BCM	M
Fisheries Iceland (2017)	Blue whiting Capelin Herring Mackerel	MW PS PS MW	Iceland	FI	NM
Schau et al. (2009)	Blue whiting Capelin European sprat	MW PS PS	Norway	FI	M, E
Tyedmers (2004)	European sprat	PS	Denmark	FI	M
Cashion et al. (2016)	Gulf menhaden	PS	USA Mexico	FI, R	M
	California pilchard	PS	Uruguay	FI, R	M
Parker and Tyedmers (2012)	Antarctic krill				

[*] According to major feed companies, Indian oil sardine oil was reported to be from Oman, which uses beach seine harvesting techniques and any boat use is manually powered. Only the data on net maintenance was used which was assumed to be similar to the traditional ring seine method used in India according to Das and Edwin (2016).

Table 2
Default boat construction and maintenance for purse seiner and trawler vessels rate per 1000 MJ of fuel used (sources; Fréon et al. (2014), Ramos et al. (2011), Vazquez-Rowe et al. (2010), Vázquez-Rowe et al. (2011), Svanes et al. (2011b)).

Input, per 1000 MJ of fuel used	Purse Seiner		Trawler (Bottom, mid water, longline)	
	VALUE	SD95	VALUE	SD95
Boat hull				
*Concrete (ballast), m^3	**6.41E-5**	1.29	**6.41E-5**	1.61
Steel (construction and maintenance), kg	**3.43**	3.27	**0.851**	4.7
*Wood, m^3	**5.09E-4**	1.18	**5.09E-4**	1.5
Engine				
*Cast iron, kg	**0.0479**	1.36	**0.0479**	1.66
Chromium steel, kg	**0.237**	1.36	**0.0536**	1.11
*Aluminium alloy, kg	**7.37E-4**	1.36	**7.37E-4**	1.66
Copper, kg	**0.0292**	1.3	**0.131**	1.11
Net/ fishing gear				
Nylon, kg	**1.24**	6.88	**0.203**	6.17
Polyethylene, kg	**0.407**	9.1	**0.0228**	6.14
Lead, kg	**0.186**	3.22	**0.0152**	1.92
Other inputs				
Paint (33% alkyd, 67% epoxy resin), kg	**0.216**	9.88	**0.0117**	1.68
Lubricating oil, kg	**0.247**	7.53	**0.0869**	1.22

[*] NB. data could not be found for all inputs and in such cases was deemed to be the same between purse seiners and trawlers although the NUSAP representativeness data was adjusted accordingly, resulting in higher uncertainty (Henriksson et al., 2013).

effort (fuel intensity) which is larger for trawler fisheries than purse seiners.

Full life cycle inventories for Peruvian anchoveta (Fréon et al., 2014), Spanish purse seiner and bottom trawlers (Vazquez-Rowe et al., 2010), North East Atlantic mackerel (Ramos et al., 2011), and Arctic krill (Parker and Tyedmers, 2012) fisheries are shown in Tables S1 to S11 in the supplementary information. Icelandic long-line, Norwegian autoline, Norwegian and Danish mixed fisheries data were taken from Fulton (2010), Svanes et al. (2011b), SINTEF (2020) and Thrane (2004) respectively, along with the proportion that each fishery type contributes to the overall national production in each country (Tables S7 and S9). Data on Spanish tuna fisheries and by-product rendering were taken from Cortes et al. (2021) with processing data from Hospido et al. (2006). SINTEF (2020) and Thrane (2004) only provided fuel intensity, antifouling emissions and refrigerant use (which was all assumed to be R134A, despite some older references declaring the now obsolete R22 and industry reports of some vessels using ammonia-based refrigerants (Shipowners Club, 2016), for each fishery type. For calculating LCIAs, where boat construction and maintenance data are not provided, they can be applied as the default values in Table 2, proportional to fuel intensity, according to the fishery type. For species/ fisheries in Table 3, only limited data were available, for fuel intensity, gear type and in the case of Almeida et al. (2013), antifouling emissions and ice use. For all other cases it was assumed that no ice was used on-board and a default value of 0.02 kg of antifouling emissions per tonne catch was applied as for Thrane (2004).

Antifouling paints composition (Table 4), was based on Fréon et al. (2014) and applied universally for use in all fishing processes. Most literature sources state the quantity of “anti-fouling emissions” in kg, but do not provide the composition.

Processing data was provided by one UK based whitefish processor from which a default process for whitefish processing was built (Table 5). Energy and fuel oil use for pelagic fish processing was obtained from SINTEF (2020) with other inputs assumed to be the same as for whitefish processing. The processing yields to fillets were taken from FAO (1989).

Rendering inventory data for anchoveta (Fréon et al., 2017) and sandeel (Danish LCA Food database, accessed 10/4/21) were horizontally averaged to provide a default process per unit raw material input

Table 3
Other fishery data as available, economic allocation to main species as shown in Table 1 (Economic allocation shown for Schau et al., 2009).

Species	Location	Source	Gear type	Fuel intensity MJ	Anti- fouling, kg	Other
Sardine	Portugal	Almeida et al. (2013)	PS	1138	0.025	ice – 45 kg
Blue whiting	Iceland	Fisheries Iceland (2017)	MW	3062	0.02	-
Capelin	Iceland	Fisheries Iceland (2017)	PS	1044	0.02	-
Herring	Iceland	Fisheries Iceland (2017)	PS	1044	0.02	-
Atlantic mackerel	Iceland	Fisheries Iceland (2017)	MW	3062	0.02	-
Blue whiting	Norway	Schau et al. (2009)	MW	2135	0.02	-
Capelin	Norway	Schau et al. (2009)	PS	2135	0.02	-
European sprat	Norway	(Schau et al., 2009)	PS	2135	0.02	-
European sprat	Denmark	Tyedmers (2004)	PS	3371	0.02	-
Gulf menhaden	USA	Cashion et al. (2016)	PS	1162	0.03	-
California pilchard	Mexico	Cashion et al. (2016)	PS	3589	0.1	-

Table 4
Antifouling paints composition (source: Fréon et al., 2014).

Substance	Quantity
Arsenic, mg/kg	3.5
Copper, g/kg	341
Nickel, mg/kg	59.5
Lead, mg/kg	349
Tin, mg/kg	390
Zinc, g/kg	96.2
Tributyltin (TBT), mg/kg	1.1
Diphenyltin, mg/kg	5.7
Dibutyltin, mg/kg	0.9
Triphenyltin, mg/kg	17.0

Table 5
Default LCI values for white fish processing per tonne of raw material input from primary data source. Figures are for a tonne of mixed white fish. (Data for pelagic fish was derived from SINTEF, 2020, electricity was 216kWh/t and kerosene was 319.6 MJ/t raw material inputs, while fillet yields were taken from FAO (1989)).

INPUTS		
Fish Raw material		
Cod, kg	318.1	
Haddock, kg	438.0	
Other*, kg	243.9	
Electricity, kWh	787.3	
Fuel oil burned in machinery, MJ	502.8	
Water, m^3	15.44	
OUTPUTS		**Allocation, %**
Processed cod products, kg	223.4	33.4
Processed haddock products, kg	192.9	28.8
Processed other products, kg	219.5	32.8
Mixed white fish by-products, kg	308.3	4.9

* Assumed to be saithe (*Pollachius virens*).

Table 6
Default rendering inventory per tonne raw material (Source; Avadí and Fréon (2015), Fréon et al. (2017), Danish LCA Food database (accessed 10/4/21)).

INPUTS	VALUE	SD95
Heat (gas burned in furnace), MJ	1670	2.03
Electricity use, KWh	19.5	5.98
Sodium hydroxide, kg	0.628	3.81
Antioxidant, kg	0.196	1.11
Copper wire, kg	0.00403	2.24
Bags, kg	0.143	1.34
EMISSIONS		
	VALUE	SD95
Total nitrogen, kg	0.149	1.98
Total phosphorous, kg	0.00214	7.29
BOD/ COD, kg	12.3	9.98
Suspended solids, kg	5.31	2.42

(Table 6). Rendering data for krill was based on Parker and Tyedmers (2012). The individual LCIs for anchoveta and sandeel rendering are provided in Tables S12 and S13, whereas krill rendering was combined with the fishing process, as it occurs on board (Parker and Tyedmers, 2012) (Table S11). Yields of MIs from the rendering process were obtained from several sources, shown in Table 7, where possible, using data that had been obtained from commercial rendering operations.

Table 8 shows the Biotic Resource Use for major MI species per tonne of fish, calculated according to Pauly and Christensen (1995). The standard deviation for the trophic level has been presented, but not BRU which must be adjusted for log normal distributions.

Table 8 shows an example of allocation values for the Spanish European Hake fishery that had blue whiting, Atlantic mackerel and Atlantic horse mackerel as by-catch. Allocation data is provided within the specific fishery tables within the supplementary information (Tables S2-S6 and S8) with price data for specific fisheries in Table S16.

Table 7
Yields of marine ingredients per 1 t of fish raw material input for key species.

Meal and oils	Source	Meal yield,%	Oil yield,%
Whole fish			
Anchoveta (*Engraulis ringens*)	Fréon et al., 2017	23.8	4.5
Blue whiting (*Micromesistius poutassou*)	Cashion et al., 2017	19.7	1.9
Capelin (*Mallotus villosus*)	Cashion et al., 2017	16.6	7.7
Atlantic herring (*Clupea harengus*)	Cashion et al., 2016	22.1	11.5
Atlantic mackerel ((*Scomber scombrus*)	Cashion et al., 2016	19.4	18.6
Norway Pout (*Trisopterus esmarkii*)	Cashion et al., 2016	20.4	11.5
Sandeel (*Ammodytes marinus*)	Danish LCA Food database, n.d	21.5	4.5
California pilchard (*Sardinops sagax*)	Cashion et al., 2017	23.0	18.0
Gulf Menhaden (*Brevoortia patronus*)	Cashion et al., 2017	21.0	16.0
Atlantic horse mackerel (*Trachurus trachurus*)	Tacon et al., 2006	23.0	6.0
European sprat (*Sprattus sprattus*)	Cashion et al., 2017	18.8	7.9
Sardine (*Sardina pilchardus*)	Cashion et al., 2017	23.0	18.0
Krill (*Euphausia superba*)	Parker and Tyedmers, 2012	14.4	0.07
Indian Oil Sardine (*Sardinella longiceps*)	Senapati et al., 2017, Pravinkumar et al., 2015	25.7	15.4
Byproducts			
Cod (*Gadus morhua*)	Cashion et al., 2017	17.0	1.7
Haddock (*Melanogrammus aeglefinus*)	Cashion et al., 2017	17.0	1.7
Atlantic herring (*Clupea harengus*)	Hilmarsdottir et al., 2020	22.5	17.0
Atlantic mackerel (*Scomber scombrus*)	Hilmarsdottir et al., 2020	22.5	17.0

Table 8
BRU values calculated according to Pauly and Christensen (1995).

Species	Trophic level	SD*	BRU, kg C / tonne
Anchoveta (*Engraulis ringens*)	2.9	0.4	8826
Atlantic herring (*Clupea harengus*)	3.4	0.1	27,910
Atlantic horse mackerel (*Trachurus trachurus*)	3.7	0	55,687
Atlantic mackerel (*Scomber scombrus*)	3.6	0.2	44,234
Blue whiting (*Micromesistius poutassou*)	4.1	0.3	139,881
California pilchard (*Sardinops sagax*)	2.8	0.1	7011
Capelin (*Mallotus villosus*)	3.2	0.1	17,610
Cod (*Gadus morhua*)	4.1	0.1	139,881
European sprat (*Sprattus sprattus*)	3.0	0.1	11,111
Gulf Menhaden (*Brevoortia patronus*)	2.2	0.1	1761
Haddock (*Melanogrammus aeglefinus*)	4.0	0.1	111,111
Indian Oil Sardine (*Sardinella longiceps*)	2.4	0.2	2791
Krill (*Euphausia superba*)	2.2	0.2	1761
Norway Pout (*Trisopterus esmarkii*)	3.2	0	17,610
Sandeel (*Ammodytes marinus*)	3.1	0.1	13,988
Sardine (*Sardina pilchardus*)	3.1	0.1	13,988

* Trophic level is on a logarithmic scale and must be factored in when calculating the SD of BRU.

Table 9
Mass and economic allocation factors applied to Spanish hake fisheries (Catch data from Vázquez-Rowe et al. (2011), price data is ten-year average prices according to FAO (2019) commodity data.

Species	Catch, kg/t	Price, $/kg	Price x catch	**Mass allocation %**	**Economic allocation %**
Atlantic Mackerel	210	0.65	135.48	**21.0**	**10.5%**
Blue Whiting,	430	1.03	443.53	**43.0**	**34.4%**
European hake	180	2.89	520.07	**18.0**	**40.3%**
Horse mackerel	180	1.06	191.12	**18.0**	**14.8%**

3.2. Life Cycle Impact Assessment

Full results of the LCIA using economic allocation (conventional impact categories, plus BRU and FIFO) are given in the supplementary information (Tables S17 and S18). Fig. 4 shows the Global Warming Potential (GWP) of selected fishmeals and terrestrial proteins. For fishmeals, the full LCIA data showed large differences between locations for the same species as well as between species, related to the amount of fishing effort required. Icelandic fisheries were generally the least fuel intensive and Danish the most intensive. The contribution to GWP from boat construction and maintenance was typically between 3% and 15% of total emissions per tonne of MI produced. Norwegian fisheries are presented in Fig. 4 unless otherwise stated as the footprint was around halfway between Icelandic and Danish fisheries in most cases. However, for herring and mackerel, Danish meals were as much as three times higher than Icelandic and Spanish meals respectively (Table S17). By-product meals generally had lower impacts than whole fish meals using economic allocation, although white fish by-product meal impacts were higher because of the fuel intensity of demersal fisheries and the low yields from rendering according to Cashion et al. (2017). All MIs had lower GWPs than the selected terrestrial ingredients presented in Fig. 4, especially when taking Land Use Change (LUC) into consideration.

4. Discussion

Results of the LCIA were broadly in agreement with other publications that present environmental impact assessments of MIs e.g., SINTEF (2020). While MIs typically have lower environmental impacts than terrestrial ingredients according to commonly applied LCA impact categories, the scope for expanding sustainable MI supplies depends on the ability to valorise underutilised seafood by-product resources (Jackson and Newton, 2016). This is likely to be a slow process due to a range of logistical and legislative factors, including decentralised processing and regional consumer product preferences (Stevens et al., 2018; Malcorps et al., 2021; Regueiro et al., 2021; Pounds et al., 2022). However, given their importance, sustainable MI supplies should remain part of the growing pool of ingredients available, with MI applications targeted strategically to where they are most effective (Kok et al., 2020).

It is clear that there is a large range of impacts related to different sources of MIs and they should not be treated as a single entity, but rather modelled individually. Clearly, low trophic pelagic species and their by-products have the lowest environmental impacts according to traditional LCA impact categories. Danish MIs tend to have much higher footprints than other European MIs, generally due to higher fuel intensity, but the data that underpins the analysis was the oldest and improvements may have taken place since, either through vessel improvements and/or fishing practices (Bastardie et al., 2010). Constant improvement continues within the fisheries sector, highlighting the importance of regularly updating LCI data. Greer et al. (2019) reported an estimated improvement in fishing boat engine efficiency of around 20% between 1950 and 2016. Improvements in technology and gears

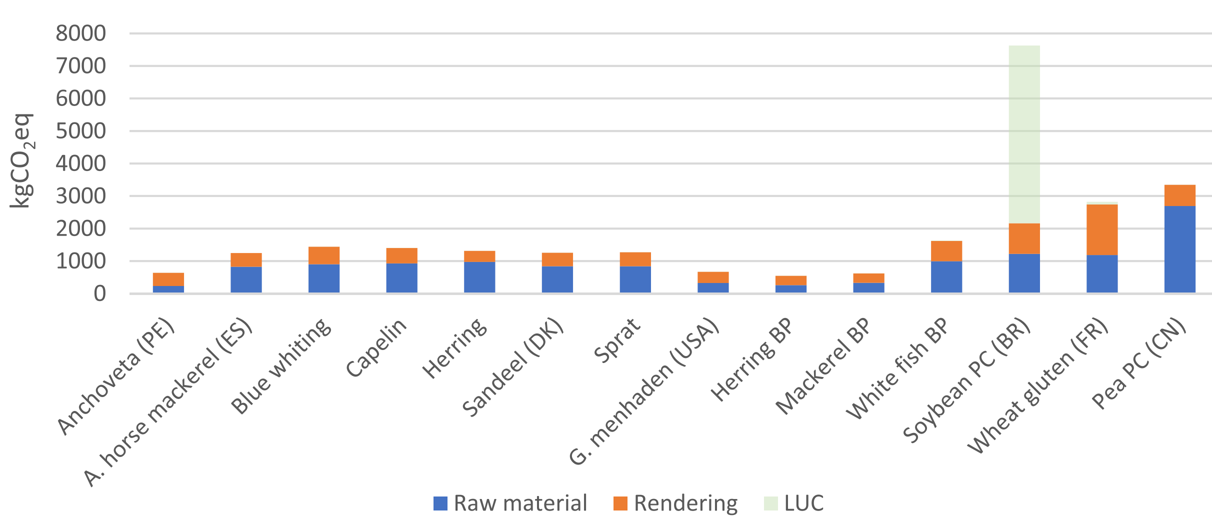

Fig. 4. Global Warming Potential per metric tonne of selected fishmeals and terrestrial protein resources (Norwegian unless otherwise stated). LUC = Land Uses Change, BP = by-product, PC = Protein Concentrate. PE = Peru, ES = Spain, DK = Denmark, BR = Brazil, FR = France, CN = China.

have also occurred and continue to be an important R&D focus, enabling more efficient targeting of fish stocks, although this has in turn often exacerbated stock decline (Marchal et al., 2006; Guijarro et al., 2017; Kang et al., 2018; Palomares and Pauly, 2019). However, Parker et al. (2018), Hornborg et al. (2020) and Ziegler and Hornborg (2014) have all demonstrated that fishing effort is closely related to stock status, which is highly variable between fisheries and species. While not all fisheries improvements are relevant to marine ingredients, there have been innovations in some purse seine fisheries such as the phasing out of metal halide lighting in favour of much more efficient LEDs to attract fish shoals (Ricci et al., 2021; Nhat et al., 2022) and more general improvements to net design and strength, navigation and fish finding equipment (Marchal et al., 2006).

Within our data set, Danish herring and mackerel meals were especially highly impacting compared to the same species from other countries. This was due to higher fuel use across all fishery types, including high fuel-intensity demersal and mixed fisheries that contribute to the overall herring and mackerel national catch. Norwegian herring and mackerel are also derived from mixed fisheries in different amounts but generally have lower fuel intensities than similar Danish fisheries (Tables S7 and S9). However, although the inclusion of BRU and FIFO metrics can give an indication of efficient use of MIs, LCA assessments do not consider the status of fisheries and the extent of their sustainable exploitation. These considerations must be made separately, perhaps using stock assessments provided by the Sustainable Fisheries Partnership (SFP, 2021). SFP assessments are linked to Marine Stewardship Council performance indicators that provide the criteria for assessments made by Marin Trust (2017) which in turn provides certification for MIs required for major international aquaculture certification organisations such as ASC (2021), BAP (2020) and GlobalGAP (2021). Certification organisations are increasingly looking to include LCA type metrics into their assessments to support climate action, so the incorporation of robust LCI data is essential. Such certification organisations have been concerned with the utilisation of "forage fish" as inputs into aquaculture for many years, typically measured by the Fish In Fish Out (FIFO) ratio (Kok et al., 2020). Certification agencies have generally encouraged the use of by-product resources in MIs by discounting their use in the various FIFO calculations employed. However, there are concerns that low yielding and inefficient by-product commodities get a "free pass" compared to more efficient feed ingredients (Kok et al., 2020). Employing FIFO alongside LCA impact categories allows comparison between trade-offs of different MIs against other ingredients in aquaculture LCAs. Although by-product MIs often have a lower environmental impact (when using economic allocation), their quality can sometimes be lower than those derived from whole forage fish, particularly regarding ash content (Goddard et al., 2008; Glencross et al., 2017; Ween et al., 2017). However, although there are concerns that quality differences may affect performance, this is not always borne out as protein and energy digestibility vary compared to forage fishmeals in diets for different aquaculture species (Chi et al., 2017; Glencross et al., 2017; Glencross et al., 2018).

The LCI data provided here is a much-needed step in providing the necessary capacity to inform better LCAs of aquaculture that can meet the various requirements for different standardised assessments such as PEFCR and others. However, the data presented in this article relies heavily on default values derived from horizontal averaging of data from similar industries, particularly: processing of fish to produce by-product raw materials; rendering data for most species; fisheries composition data and boat construction and maintenance for various fishery species across broad geographies. A specific data gap exists on purification of fish oil that may contain contaminants, which is especially a problem where fisheries are located close to heavily industrialised areas such as north European sea routes (Aidos, 2002; Einarsson et al., 2019). While this inventory is a much needed improvement on existing data, representing an estimated 48% of global supplies according to FAO (2019), better primary data on Asian fisheries would be desirable. Chinese, Thai, Vietnamese and Japanese fisheries constitute a further 26% of global MI supplies (FAO, 2019) and considering the contribution of Asian aquaculture to global seafood supplies, it should be regarded as a matter of priority to characterise its supply chains.

There is also growing concern over accumulation of microplastics in fishmeal which may also require addressing in the future (Gündoğdu et al., 2021). LCIs for MIs could be much improved with further primary data collection, particularly from fish processing and rendering and should be a priority for the industry.

5. Conclusion

As the demand for aquaculture produce increases, there are considerable efforts to reduce the reliance on MIs in aquafeeds. However, MIs will probably remain important and there is potential to increase the pool of sustainable MIs through continued fishery management and valorising underutilised fishery and aquaculture by-products. This article provides the ability to include more holistic sustainability assessments of MIs and has demonstrated that there are considerable sustainability trade-offs between aquafeed ingredients that should be taken into account when assessing aquaculture nutrition. However, a lot more work is required to improve and widen the database to include global MI supplies that are important for world aquaculture production.

Author statement

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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

Selected data will be made available on request

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Appendix A. Supplementary data

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