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Fish as Feed: Using the nutrient Fish In: Fish Out ratio (nFIFO) to enhance nutrient retention in aquaculture

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ABSTRACT

The aquaculture industry is often criticised for its use of "fish as feed", due to the limited stocks of fish used as marine ingredients (MIs). Several efforts to measure the efficiency of wild marine fish inputs into aquaculture have used versions of the Fish In: Fish Out metric (FIFO), the ratio between fish biomass included in aquafeeds compared to the biomass of fish produced from aquaculture. However, FIFO metrics overlook the retention of nutrition from those resources to the final farmed product, particularly omega-3 long chain polyunsaturated fatty acids (LC-PUFAs) that are concentrated in MIs and a central reason for their continued use in aquafeed. We introduce the nFIFO ratio to measure nutrient flows from marine resources and to aid improved retention of nutrients in aquaculture. Using literature values for LC-PUFA content in different feed fish species, MIs and farmed salmon, we quantify the retention of LC-PUFAs. We found that the mean retention of LC-PUFAs from feed fish to salmon was 37.4 %, giving a nFIFO of 2.17. Applying economic allocation principles as used in Life Cycle Assessment resulted in fish oil having a higher nFIFO burden but favoured the use of processing by-products as raw materials in MIs. We tested these principles using sensitivity analysis by 1) incrementally replacing whole fish meals and oils for their by-product counterparts, and 2) raising the price of fish oil in relation to meal. nFIFO was much improved by substituting whole fish derived MIs with those from processing by-products and highly correlated to rising fish oil prices. nFIFO is dependent on high-resolution feed data, as our study revealed high variation in feed fish nutritional content related to various seasonal and environmental factors that affect the outcome of the calculations. We provide an Excel file to aid stakeholders calculate nFIFO and other FIFO metrics.

1. Introduction

Aquatic food (mostly fish, molluscs and crustaceans from the marine or freshwater environment) have been central to global food security and the provision of essential nutrition throughout human history (Fulton et al., 2018). The omega-3 (n-3) long-chain polyunsaturated fatty acids (n-3 LC-PUFAs) docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are essential for brain development (Innis, 2008) and cardiovascular health (Holub and Holub, 2004) are of particular importance in marine-sourced food. Aquatic foods contribute the majority of global DHA and EPA intake (Calder, 2018; FAO, 2022; Hicks et al., 2019; Spiller et al., 2019; Tacon and Metian, 2017) as aquatic foods are, at present, our only reliable and dependable source of these two critical n-3 LC-PUFAs. This stems from the fact that n-3 LC-PUFAs are synthesised by marine phytoplankton, and then bioaccumulated up through the marine food web (Hamilton et al., 2020). The result is that small, pelagic oily fish such as anchovies, sardines, herrings and mackerels are amongst the richest sources of n-3 LC-PUFAs available to humans (Willer et al., 2024; Romotowska et al., 2016; Loaiza et al., 2020). Farmed fish such as salmon can also be a good source of n-3 LC-PUFAs, but only if they are fed a diet rich in n-3 PUFAs (de Roos et al., 2017). Small oily fish are typically included in the diets of many farmed fish in the form of 'marine ingredients' (MIs), which are most commonly meals and oils made from cooking, separating, drying

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and grinding of these small oily fish, and increasingly the by-products from fish processing, that now contribute to around a third of global marine ingredient supply (Jackson and Newton, 2016). Additionally, there is an emerging market of n-3 LC-PUFA-rich algal oils that are beginning to gain market traction (Santigosa et al., 2023).

The inclusion of MIs in aquafeed stimulates senses, consumption and digestibility, and provide essential nutrients for cultured animal growth and welfare (Newton et al., 2023). However, there is a debate around the efficiency of feeding marine ingredients to farmed fish, particularly those derived from species often targeted for human consumption, such as herrings, mackerels, sardines and anchovies (Willer et al., 2022; Willer et al., 2024). Several studies demonstrate that nutrient retention is more efficient if marine resources are directly consumed by people (Willer et al., 2024). However, it is rare for the whole fish to be consumed, meaning that processing and preparation of fish is also critical to retain the nutrition contained in otherwise inedible fractions. Therefore, efforts need to be made throughout the human consumption supply chain, including in the processing sector to improve the retention and availability of valuable nutrients. This could partly be achieved through use of processing by-products in the aquafeed industry (Hamilton et al., 2020; Stevens et al., 2018; Malcorps et al., 2021).

The marine ingredients industry pre-dates the growth of modern intensive aquaculture, with the peak in the fisheries that supply marine ingredients production occurring during the 1990s. Prior to use in aquaculture, MIs were used for various applications but predominantly for companion animals, other livestock feeds, fertiliser and fuel (Newton et al., 2014). However, the growth of aquaculture through the 1990s into the new millennium and associated rapid uptake of the finite MI supply (around 90 % of oil and 70 % of meal is currently used by aquaculture), has raised concerns over the sustainability of MI use in aquaculture (Naylor et al., 2000; Shepherd et al., 2017; Tacon and Metian, 2008). The supply is further challenged by reliability issues, for example, increasingly frequent and severe El Nino events that have on multiple occasions crashed the large anchovy stocks (Merino et al., 2010) that contributes up to a third of supplies (Tacon and Metian, 2009). Such volatility has been tempered by increasing contributions from the fisheries and aquaculture processing industry that supply by-product raw materials for rendering (Newton et al., 2023; Glencross et al., 2024). MI companies and feed producers note that most fisheries that supply raw material for the industry are well managed, with around 70 % certified using criteria from the Sustainable Fisheries Partnership (SFP) under the Marin Trust scheme (Marin Trust, 2023), but the situation is shrouded in complexities from global market and logistics perspectives. There are undoubtedly cases where global market forces could outweigh local demand. For example, high profile cases where MI companies compete for supplies of food-grade fish for export that were already established as important contributors to local food security in low- and middle-income nations, such as in West Africa (Pauly, 2019; Hicks et al., 2019) and may become of increasing concern as global demand for aquatic food grows. The limited supply of marine ingredients has led to economic pressures, environmental concerns, and poor public perception (Naylor et al., 2009), contributing to salmon feed manufacturers decreasing the inclusion of marine ingredients in aquafeed and the shift towards cheaper, crop-based ingredients (Aas et al., 2022). Farmed salmon is the largest consumer of fish oil and this shift has led to a decline in n-3 PUFA content (Sprague et al., 2016) and arguably compromised fish welfare (Daniel, 2018), while shifting sustainability concerns from the oceans onto the land, potentially adding pressure to the land-based food production systems (Fry et al., 2016). Therefore, if aquaculture is to continue to grow and meet a complexity of sustainability, human nutrition and fish health and welfare goals, particularly for carnivorous species, more efficient use of MI is required.

Despite incentives to increase direct consumption of small fish, e.g. (Fréon et al., 2013), there are strong and valid reasons for the continuation of the marine ingredient sector, not least their nutritional advantages in livestock feeds (Newton et al., 2023). Furthermore, some of the species directed to marine ingredients are unsuitable for direct human consumption, such as sandeel (*Ammodytes marinus*) or they may have low market appeal such as anchovy (*Engraulis ringens*) (Fréon et al., 2013). There is also considerable scope to further increase new marine ingredient raw materials from processing by-products (Jackson and Newton, 2016). For most fish species, fillet yields range between 45 % to 55 % (FAO, 1989), leaving highly nutritious 'trimmings' unused, but markets and scalability for circular economy incentives remain a challenge. Logistics of storing and transporting highly perishable seafood commodities, including those processed on-board fishing vessels, are also a considerable issue in some communities and locations (Newton et al., 2014; Rustad et al., 2011; Malcorps et al., 2021). Ideally, food-grade fish would be consumed directly by people, either whole or the edible portion, with the by-products directed to animal feeds to maximise nutrient retention in a broader circular economy supported "food landscape" (Campanati et al., 2021; Pounds et al., 2022). While some recent papers, e.g. Majluf et al. (2024) point out that the use of by-products does not result in any overall reduction in wild fish capture, it does reduce waste and increase the supply of much needed feed resources without added pressure on fisheries (Glencross et al., 2024). Production volumes from the fisheries that underpin MIs have already reduced significantly since the 1990s as pointed out by Majluf et al. (2024) and Newton et al. (2023). Consequently, it is important that the sector recognises the need for both improving raw material efficiency and nutrient retention as global populations continue to increase and demand better nutritional security.

In this paper, we build on previous work, underscoring potential efficiency gains in nutrient retention for salmon production (Willer et al., 2024) to develop a nutrient retention scoring tool for the use of fisheries resources, based on the well-established Fish In: Fish Out (FIFO) metric (Jackson, 2009; Kok et al., 2020; Naylor et al., 2009; Tacon and Metian, 2009) which we are terming nFIFO. Although there are well established metrics for general nutrition efficiency of livestock production, such as Feed Conversion Ratio (FCR), Protein Efficiency Ratio (PER) and others, there have been few attempts to develop a nutritionally sensitive metric that is linked specifically to aquaculture. However, Crampton et al. (2010) introduced the concept of a Marine Nutrient Dependency Ratio (MNDR) which focussed particularly on marine protein and oil. However, the method was linked to retention of nutrients from feed rather than fish raw material and not intrinsically linked to the FIFO metric. Similarly, Ytrestøyl et al. (2015) used a mass balance approach to demonstrate the retention of n-3 LC PUFAs from feed to salmon in the Norwegian industry but used global industry averages for marine ingredient yields and for lipid contents of meals. When considering n-3 LC PUFAs, neither of these approaches were linked to the amount of fish raw material and consequently did not effectively address the problem of dividing the fish resources between meal and oil and the nutritional content within them. A key development of the FIFO metric was to introduce economic allocation, using standard Life Cycle Assessment (LCA) methodologies (termed eFIFO), effectively aligning FIFO with Product Environmental Footprint Category Rules (PEFCR) compliant LCA and more effectively incorporating the contribution of by-product fractions into the calculation (Kok et al., 2020). The introduction of LCA principles overcomes disparities between, yields and inclusion rates that led to skewed interpretations in earlier forms of FIFO that reported on the limiting ingredients without accounting for left-over meals or oils that could be further utilised (Kok et al., 2020). The nFIFO tool builds on eFIFO (from now on, $_{e}$FIFO) methodology and thus enables the aquaculture, and potentially other industries, to measure effectively, the retention of key nutrients from marine ingredients, such as LC n-3 fatty acids, and adjust their formulations and delivery of feed strategically, to deliver better nutrition to people, by maximising the use of all marine resources. Hence, we have produced a demonstration of the nFIFO metric for EPA + DHA retention from forage fish to finished product. In theory, the tool could be used for any nutrient and species of cultured animal, depending on the availability of data.

2. Methods

Using the nutritional content of forage fish and by-products used in salmon diets according to (Skretting, 2018), marine ingredients according to data sources set out in Table 1, and farmed salmon (Aas et al., 2019), we developed a series of equations to trace the pathways of EPA + DHA from wild-caught fish used in marine ingredients to final farmed salmon at the farm gate. The EPA + DHA content of whole farmed salmon was taken as 1.16 % (wet-weight) from (Aas et al., 2019). Yields of FM and FO were taken from (Newton et al., 2023) and FCR was assumed to be 1.3 according to industry average data from (Aas et al., 2019). For fishmeal and fish oil price per tonne, we took the three-year average for each on the global market, US$1785 for meal, and US$4260 for oil (OECD-FAO, 2018; Glencross et al., 2024). We took the value of fish processing by-products to be 10 % of all co-products, according to (SINTEF, 2020) (for the purposes of this article, co-products are defined as any product produced from a single multi-functional process, where by-products are co-products that are not the target of production and typically of low value). However, due to increasing competition for by-products, the 10 % figure may be considered to be quite low.

Nutritional content of whole fish, fish by-products, fishmeal and fish oil from the species included in (Skretting, 2018) was sourced from eighty-one publications (detailed in Table S1). The horizontal averaging methodology for LCA data (Henriksson et al., 2013) was applied to provide weighted averages and uncertainty across the literature sources. “White fish” meals included data from cod, haddock and Alaskan pollock pooled together as this is common practice in white fish processing plants and reflects the inclusions within the Skretting (2018) data.

We calculated nFIFO using mass (using the formulae from Jackson (2009): n_mFIFO), and economic allocation, based on the $_e$FIFO method developed by (Kok et al., 2020): n_eFIFO. The overall nFIFO score is a function of the retention of nutrients in MIs and that retained in the cultured animal when fed feed containing MIs. To calculate an economically adjusted n_eFIFO, we use allocation factors for both the raw material (i.e. those originating from processing by-products), EQ1, and between fishmeal and fish oil from the rendering process, EQ2. The economically adjusted fishmeal and fish oil yields can then be calculated according to EQ3. Retention of nutrients from raw material to MI, and from MI to the cultured animal, are calculated according to EQ4 and EQ5 respectively with the overall n_eFIFO calculation shown in EQ6. Standard deviations for nFIFOs were calculated based on the variation in individual EPA + DHA content for raw materials and marine ingredients.

Eq. (1) Economic allocation for raw materials (by-product inclusion) from fish processing

$$A_{rm} = \frac{Y_{BP} \times P_{BP}}{(Y_{BP} \times P_{BP}) + \sum (Y_{CP} \times P_{CP})} \tag{1}$$

Eq. (2) Economic allocation for fishmeal and fish oil from rendering process, e.g. for meal

$$A_m = \frac{Y_m \times P_m}{(Y_m \times P_m) + (Y_o \times P_o)} \tag{2}$$

Eq. (3) Allocation adjusted yield (meal)

$$Y_{m_a} = A_m \times (Y_m + Y_o) \tag{3}$$

Eq. (4) Retention in MIs

$$R_{MI} = \sum \frac{(Y_m \times \omega3_m) + (Y_o \times \omega3_o)}{\omega3_{rm} \times A_{rm}} \tag{4}$$

For economic allocation, substitute the FM and FO yields (Y_m and Y_o) for the allocated adjusted yield (Y_{m_a} and Y_{o_a}) in Eq. (4).

Eq. (5) Retention in salmon

$$R_s = \frac{\sum [(I_m \times \omega3_m) + (I_o \times \omega3_o)]}{\omega3_s} \times FCR \tag{5}$$

Eq. (6) nFIFO

$$\frac{R_s}{R_{MI}} \tag{6}$$

Y = yield, %
I = inclusion, %
ω3 = EPA + DHA content as g/100 g FAs
P = price, US$
A = allocation factor as a %
R = retention, %
s = salmon
m = meal
o = oil
rm. = raw material
MI = marine ingredient
BP = processing by-products (used as raw materials for MIs)
CP = processing co-products (i.e. all other co-products apart from by-products used as raw materials)

Table 1
Inclusion of different marine ingredients in salmon diets according to (Skretting, 2018) (2018).

	Proportion of diet %	
Whole Fish	Meals	Oils
Anchovy	0.69 %	2.88 %
Blue Whiting	4.02 %	1.20 %
Capelin	1.07 %	0.81 %
Herring	0.53 %	0.39 %
Atlantic horse mackerel	0.01 %	0.00 %
Atlantic mackerel	0.10 %	0.02 %
Norway pout	0.11 %	0.11 %
Sandeel	2.18 %	0.44 %
Sprat	0.97 %	1.31 %
TOTAL	**9.68 %**	**7.16 %**
By Products	**Meals**	**Oils**
Capelin BP	0.31 %	0.11 %
Herring BP	1.67 %	1.94 %
Mackerel BP	0.46 %	0.64 %
Horse mackerel BP	0.01 %	0.00 %
Whitefish BP	0.04 %	0.00 %
TOTAL	**2.49 %**	**2.69 %**
GRAND TOTAL	**12.17 %**	**9.84 %**

2.1. Sensitivity analysis

To test the sensitivity of the model to incremental changes, and how the tool could be applied to develop strategies to improve nutrient retention, we employed two scenarios. In our first scenario (S1), the supply of MIs is partially replaced and bolstered by a large increase in the supply of processing by-products as more people consume wild fish directly and processing efficiencies improve. We investigated the replacement of whole, wild fish-derived meals and oils within salmon feed with by-products. Our model incrementally takes out meal and oils from mackerel, herring, anchovy, blue whiting, and finally all other whole fish meals and oils, replacing them with by-product meals and oils, predominantly from mackerel, herring, and mixed whitefish, but with small inclusions from capelin and horse mackerel by-products. The scenario assumes that the supplies of raw materials are sufficient to maintain the necessary inclusions for continued growth in the salmon sector. All marine ingredient compositions had the same EPA + DHA content, but varied in their overall marine ingredient inclusion, with more oil inclusion in many of the compositions compared to the baseline. The experimental compositions can be seen in Table 2. The second scenario (S2) assumed that continuous growth in aquaculture results in

Table 2
Marine ingredient compositions for sensitivity analysis in Scenario 1, with increasing substitution of whole fish meals and oils for by-product meals and oils.

	Baseline		no Mackerel		no herring		no anchovy		no B Whiting		BP only	
WHOLE FISH	Meal	Oil	Meal	Oil	Meal	Oil	Meal	Oil	Meal	Oil	Meal	Oil
Anchovy	0.69	2.88	0.69	2.88	0.69	2.88	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Blue Whiting	4.02	1.20	4.02	1.20	4.02	1.20	4.02	1.20	**0.00**	**0.00**	**0.00**	**0.00**
Capelin	1.07	0.81	1.07	0.81	1.07	0.81	1.07	0.81	1.07	0.81	**0.00**	**0.00**
Herring	0.53	0.39	0.53	0.39	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Atlantic horse mackerel	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	**0.00**	**0.00**
Mackerel	0.10	0.02	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Norway pout	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	**0.00**	**0.00**
Sandeel	2.18	0.44	2.18	0.44	2.18	0.44	2.18	0.44	2.18	0.44	**0.00**	**0.00**
Sprat	0.97	1.31	0.97	1.31	0.97	1.31	0.97	1.31	0.97	1.31	**0.00**	**0.00**
By-products												
Capelin	0.31	0.11	0.31	0.11	0.31	0.11	0.31	0.11	0.31	0.11	**1.00**	**0.50**
Herring	1.67	1.94	1.67	1.94	**2.22**	**2.26**	**2.22**	**4.45**	**2.22**	**5.00**	**2.25**	**6.00**
Mackerel	0.46	0.64	**0.60**	**0.66**	**0.60**	**0.66**	**1.30**	**4.00**	**1.30**	**4.69**	**2.50**	**7.00**
Atlantic horse mackerel	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	**1.00**	**0.35**
Whitefish	0.04	0.00	0.04	0.00	0.04	0.00	0.04	0.00	**4.50**	**0.00**	**5.50**	**0.00**
INCLUSION TOTAL	12.18	9.84	12.22	9.84	12.23	9.77	12.24	12.42	12.68	12.46	12.25	13.85
INCLUSION BPs	2.49	2.69	2.63	2.71	3.18	3.03	3.88	8.56	8.34	9.80	12.25	13.85
INCLUSION WHOLE	9.68	7.15	9.59	7.13	9.05	6.74	8.36	3.86	4.34	2.66	0.00	0.00
% Baseline inclusion	**100.00**	**100.00**	**100.34**	**99.95**	**100.45**	**99.21**	**100.50**	**126.16**	**104.15**	**126.56**	**100.60**	**140.70**
EPA DHA content	3.10		3.10		3.10		3.10		3.10		3.10	
EPA DHA % target	100.00		100.06		99.99		100.03		100.03		99.95	

severe pressures on the limited supply of marine ingredients, particularly in relation to fish oil as the more limiting of the two ingredients, leading to a significant price hike for fish oil on the world market compared to fishmeal. The model was applied to increasing prices of oil up to US$14000 while keeping the price of fishmeal at US$1785. Mass and economically allocated FIFO and nFIFO were calculated for both scenarios as above.

3. Results

The lipid and EPA + DHA content of raw materials, and various meals and oils for different species, can be seen in Table 3. There was a large amount of variation within and between species, due to many factors as discussed below. Data were found for all species and associated marine ingredients except for the by-products from capelin.

For whole fish, the highest lipid content was found in *scombrid* and *trachurus* mackerels but highest EPA + DHA in lipids (g/100 g lipid) was found in anchovy. Overall, the highest EPA + DHA content in fish tissue was found in *scombrid* mackerels (%WW) and lowest in blue whiting. Out of the by-product fractions, herring had the highest lipid content but *scombrid* mackerel by-products had the highest EPA + DHA (%WW). Many of the derived fish meals had lipid contents of over 10 % along with high EPA + DHA, leading to EPA + DHA content as high as 3.36 % (WW) in mackerel meals. In contrast, blue whiting and white fish by-product meals had EPA + DHA contents of less than 1.0 % (WW). The highest EPA + DHA content was in anchovy oil at 30.46 g/100 g lipid.

Calculations revealed an overall retention of around a 94.5 % of EPA + DHA from forage fish raw materials to marine ingredients and an overall retention of 38.6 %. The n_mFIFO is essentially the inverse of the retention score from raw material to finished product and was calculated to be 2.59 (±0.60) for EPA + DHA. The n_eFIFO, taking a 3-year average of fishmeal (US$1785) and fish oil (US$4260) prices and a by-product value of 10 % of all processed co-products, was calculated to be 2.17 (±0.47). Fig. 1 shows the flows of EPA + DHA from raw materials through MIs to final salmon product. The "Left-over MIs" flow is mostly fishmeal that is not required within the salmon diet but are left-over co-products of fish oil production that is included.

The following results use various forms of FIFO which have been defined above, but for clarity are presented in Table 4.

Table 3
Lipid and EPA + DHA content of main fish species and by-products for reduction, and derived fishmeals and fish oils, EPA + DHA content of oil as g/100 g of total lipid, lipid and EPA + DHA content of fish as %WW. Source data is detailed in Table S1.

	Whole fish								Marine ingredients			
Whole Fish	Lipid %	SD	EPA + DHA	SD	Fish EPA DHA	SD	Meal lipid %	SD	Lipid EPA DHA	SD	Meal EPA DHA	SD
Anchovy	6.02	3.49	33.66	5.70	2.03	0.60	9.57	1.76	30.46	6.81	2.03	0.29
Blue Whiting	3.00	0.86	22.36	6.33	0.67	0.40	8.84	0.97	18.26	2.52	0.67	0.18
Capelin	12.0	5.53	15.69	2.04	1.88	0.48	11.07	1.93	20.65	7.14	1.88	0.39
Herring	13.2	4.35	12.95	6.57	1.70	0.61	8.95	1.90	11.90	2.51	1.70	0.30
Jack mackerel	10.2	3.51	19.69	5.28	2.01	0.44	9.34	1.25	20.58	7.21	2.01	0.37
Mackerel	19.2	4.52	17.50	4.11	3.36	0.33	7.72	2.68	17.14	3.39	3.36	0.40
Norway pout	5.85	1.10	23.41	4.39	1.37	0.27	11.59	2.82	24.58	6.55	1.37	0.36
Sandeel	7.88	1.54	25.09	4.84	1.98	0.27	8.78	0.25	26.68	4.52	1.98	0.17
Sprat	12.1	3.10	19.86	5.93	2.40	0.39	11.47	2.93	22.74	7.29	2.40	0.41
By Products												
Capelin BP					1.81*				14.35*		1.59*	
Herring BP	16.0	3.73	12.78	4.03	2.05	0.39	9.00	3.03	13.75	4.20	2.05	0.45
Mackerel BP	13.4	10.3	15.83	2.89	2.12	0.79	14.30	3.18	17.34	4.21	2.12	0.33
Jack mackerel BP	10.3	0.23	13.60	1.37	1.40	0.10	10.00	0.57	20.58	2.03	2.06	0.19
Whitefish BPs	2.85	0.32	23.43	5.03	0.67	0.24	9.01	1.54	22.07	10.11	0.67	0.49

[*] NOTE: no data on capelin by-products were found and values were estimated from whole fish and associate MI averages.

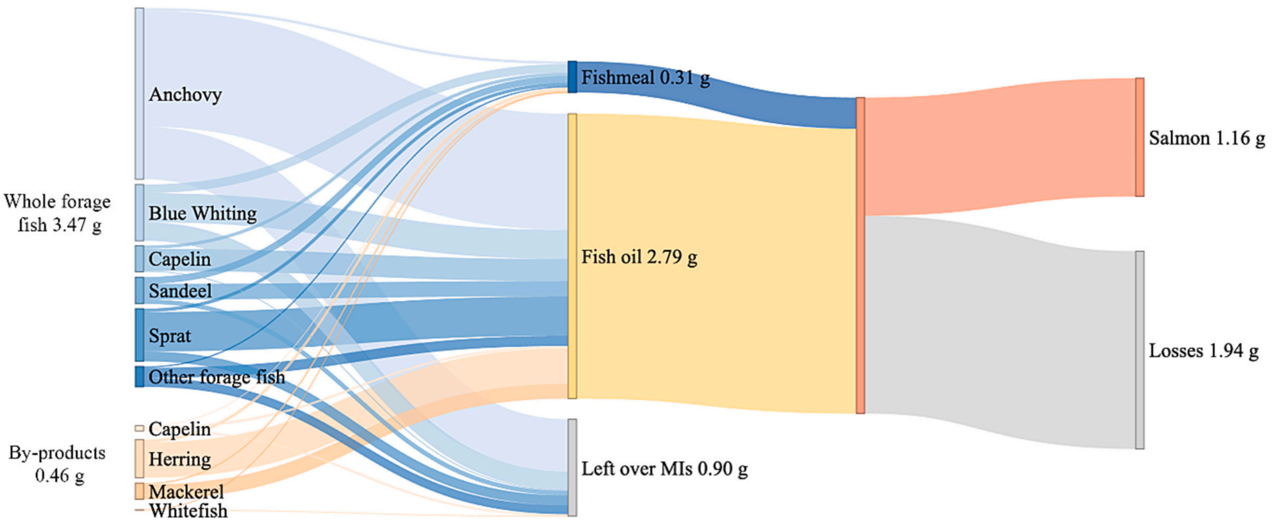

Fig. 1. EPA + DHA pathways from forage fish and fishery by-product resources through marine ingredients to final, whole aquaculture product, linked to 1.16 g/100 g in final salmon product.

Table 4
Fish In: Fish Out (FIFO) ratios as defined in this paper by allocation and scope.

	Scope	Allocation	Notes
${}_{m}$FIFO	Fish biomass	Mass	Based on Jackson (2009) but including inputs from by-product resources
${}_{e}$FIFO	Fish biomass	Economic	According to Kok et al. (2020), with “embodied fish” determined by the proportionate value of meals, oils and raw material sources (e.g. by-products)
n_{m}FIFO	Nutritional content	Mass	Using nutritional content of raw materials, MIs and salmon content applied to the Jackson (2009) formula and including by-products
n_{e}FIFO	Nutritional content	Economic	Using nutritional content of raw materials, MIs and salmon content applied to “embodied fish” determined by the proportionate value of meals, oils and raw material sources according to Kok et al. (2020)

3.1. *Substitution of forage fish MIs for by-product MIs*

Our scenario modelling revealed effects of by-product utilisation (S1) and fish oil limitation (S2) on nutrient retention. Substitution of whole fish meals and oils with by-products affected ${}_{e}$FIFO and n_{e}FIFO markedly (Fig. 2). Substitution of both mackerel and herring whole fish marine MIs with by-product-derived meals and oils had little effect on n_{e}FIFO as they had low inclusion (<5 %) of total MI each and relatively low EPA + DHA content. Substitution of anchovy marine ingredients with by-products decreased n_{e}FIFO from 1.92 to 1.63, most likely due to the large inclusion of EPA + DHA rich anchovy oil (29.23 % of total marine oils) in the baseline diet. Removing blue whiting ingredients had less of an effect on n_{e}FIFO. Most blue whiting inclusion is meal which has low EPA + DHA content (Table 3) and most of the effect is from removing the oil, which makes up 12.2 % of total marine oils in the baseline diet and has an average EPA + DHA content. Replacement of the remaining whole fish meals and oils has a dramatic effect and reduces n_{e}FIFO to 0.23 overall. n_{m}FIFO is also reduced as a result of increased yields of marine ingredients from by-products, but also increased uncertainty due to data limitations around by-product meals and oils that increase the overall retention level.

The effect on ${}_{m}$FIFO and ${}_{e}$FIFO is more contradictory. As more whole fish meals and oils are replaced, the overall MI inclusion increases as particularly anchovy oil is much higher than by-product oils in EPA and DHA, so more are required to meet the target content of 3.1 g/100 g in the diet, although this is partially offset by high yields of fish oil from particularly herring and mackerel by-products. Consequently, the higher inclusion of marine ingredients from by-products results in a slightly higher ${}_{m}$FIFO, but much lower ${}_{e}$FIFO because of the price differential between processing by-products and other co-products from the processor.

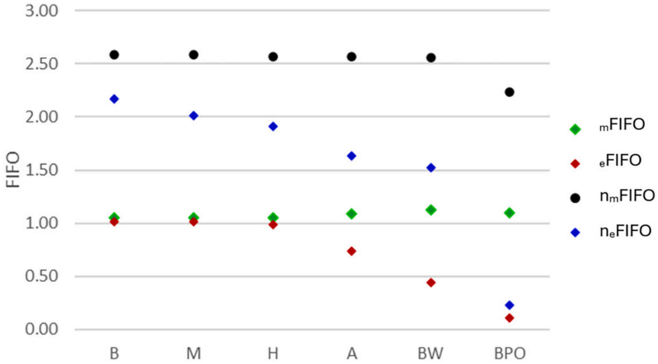

Fig. 2. Effect on FIFO ratios of incremental replacement of whole fish meals and oils with by-product meals and oils. Diets: B = baseline, then left to right cumulative replacement of M = mackerel, H = herring, A = anchovy and BW = blue whiting. BPO = by-product only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. *Fish oil price*

The price of oil does not affect the mass allocated standard ${}_{m}$FIFO or n_{m}FIFO as the inclusion rate of various marine ingredients is unchanged. Only the economically allocated (n)${}_{e}$FIFO ratios are affected (Fig. 3). Unsurprisingly, (n)${}_{e}$FIFO increases as the relative price of fish oil increases because the inclusion of fish oil in the diet is larger than the rendered yield from the raw materials, meaning that there is effectively more “embodied fish” in the diet as the relative oil price increases. n_{e}FIFO increases faster than ${}_{e}$FIFO with increasing oil price which is the combined effect of the oil yield, inclusion rate and EPA + DHA content within fish oil. However, oil has to rise to eight times that of meal for economically allocated and mass allocated nFIFO to match because of the effect of inclusion of by-products in the diet.

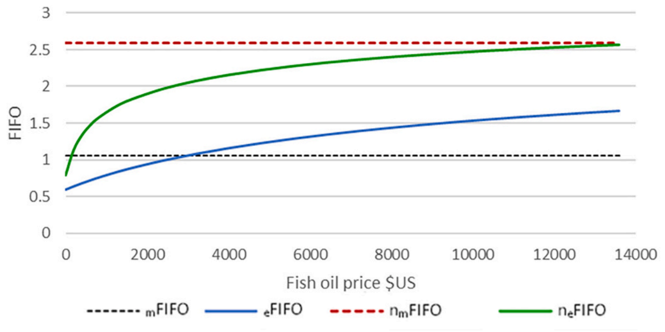

Fig. 3. The effect of increasing relative price of fish oil compared to fishmeal (US$ 1785 constant) on (n)FIFO scores, using consistent baseline marine ingredients inclusions.

4. Discussion

The aim of nFIFO is that stakeholders can use the tool for a quick assessment to aid the strategic use of MIs within aquaculture production cycles, to optimize retention of key nutrients. The results of implementing the nFIFO tool show that it could be useful for feed manufacturers, producers and other stakeholders in the aquaculture sector to improve nutrient retention and develop strategies to do so. This may include targeting various key parts of the production cycle to improve various management outcomes, including better health management of the fish (Santigosa et al., 2023) and the use of finishing diets to increase LC n-3 fatty acids prior to slaughter (Bell et al., 2004). Our results of 37.4 % EPA + DHA retention from feed to whole salmon is lower than reported by (Aas et al., 2022). However, the source of the data on feed nutritional content used in that paper is unclear as feed samples were not analysed, data provided by feed companies was unvalidated and calculations were based on methodology from Ytrestøyl et al. (2015), that used global averages as detailed above. We believe that our data synthesis of the nutritional content of fish and feed spanning eighty-one literature sources is robust (Table S1). However, the variation within the nutritional content of both the raw materials used for reduction and the marine ingredients themselves cannot be ignored and this could have a considerable effect on nutrient retention and the results from the tool. The 94.5 % retention level from raw material to marine ingredients in our model suggests that the data is robust, however this may not necessarily reflect well on how the industry targets fisheries. Several authors have highlighted seasonal variations in lipid and EPA + DHA content in different species, mostly linked to sexual maturation (e.g. Røjbek et al. (2014), Danielsen et al. (2016), Bandarra et al. (2001)) but also geographical differences (e.g. Romotowska et al. (2016), Falch et al. (2006)) Fisheries operate to geographical and seasonal quota systems that are designed to maximise catch volumes within their sustainable limits (Bórquez and Hernández, 2009). Löfstedt et al. (2024) estimated fishing rates for Atlantic mackerel based on maximum nutritional yield, finding that an autumn fishery provided higher amounts of lipids and n-3 fatty acids, whereas vitamin D$_3$ and calcium were maximized in winter fishery, but generally fishing rates for maximum nutritional yield (FMNY) were equal to, or lower than, those for maximum sustainable yield.

Our analysis is a significant improvement on previous versions of FIFO in several ways. Previous versions have used global averages for yields of fishmeal and fish oil, whereas we have used individual yields throughout. The weighted averages for fishmeal and fish oil for the inclusions in our analysis were 20.1 % and 5.4 % respectively, compared to the global average of 22.5 % and 5.0 % in other analyses (Majluf et al., 2024). The nFIFO tool is the next step in the evolution of FIFO to recognise quality issues that underpin a key reason for MI inclusion in aquafeeds. n$_e$FIFO and $_e$FIFO can both be used as complementary tools to standard LCA indicators as they follow the same principles of allocation. In that way, trade-offs between carbon, land, water and other footprints can be compared alongside the use of fisheries resources and potentially linked to nutritional outcomes which is becoming a bigger focus in recent food LCAs (e.g.(Weidema and Stylianou, 2019, Stylianou et al., 2015, Sonesson et al., 2019). Economic allocation within FIFO calculations favours greater utilisation of by-products, which has already become a key driver in the industry to expand the supply of sustainable raw materials for MIs. If used in conjunction with LCA indicators, the overall sustainability of these resources can be more comprehensively assessed, in relation to fuel intensity of the fisheries from where the raw material is derived, for example.

The effect of allocation is clear in both sensitivity analyses where increasing price of oil steadily increases $_e$FIFO and n$_e$FIFO. Aqua-grade fish oil prices reached an unprecedented US$8200 per tonne in the latter part of 2023 (Glencross et al., 2024) due to a number of factors leading to low quotas set for anchovy during 2023 and a much-reduced global supply (Fish Oil and Meal World, 2024). The use of economic allocation in raising the nFIFO ratio is therefore a good reflection of the real time pressures on fishery stocks. Similarly, using by-product derived meals and oils can substantially reduce both $_e$FIFO and n$_e$FIFO and become a driver to encourage their use. The tool does not necessarily aid in the redirection of edible fish such as mackerel or herring to human consumption, but it does discourage their direct use in feed in favour of their processed by-products. The value of by-products was set at 10 % of all processing co-products according to (SINTEF, 2020). However, by-product values vary regionally and according to the raw material. Increasing competition in recent years, including from the companion animal sector as well as marine ingredients, has been pushing up the price of by-product resources (Boland et al., 2013; Hayes, 2023). In such circumstances, $_e$FIFO and n$_e$FIFO will increase according to the level of by-products included within the diet and their associated increase in value. In turn, higher prices for by-products at the processor would be expected to encourage their upscaling and prevent waste. However, only when by-product MIs are included at high levels is it possible to achieve an n$_e$FIFO of lower than 1.0, which means in other scenarios, valuable n-3 LC PUFAs may be being lost, especially when including whole forage fish species that are suitable for direct human consumption.

In addition to LC n-3 PUFA, fish are important dietary sources of vitamins B12 and D, and of a range of other essential micronutrients (Löfstedt et al., 2021, Willer et al., 2024). Recently, a decision framework was developed to effectively select nutrients in aquatic food research based on their importance for human physiology, nutritional needs of the target population, and nutrient availability in aquatic foods compared to other accessible dietary sources (Zamborain-Mason et al., 2023). At the outset of this work, we intended to model vitamin D, vitamin B12 and iron as important nutrients in aquatic foods as identified by (Willer et al., 2024). For example, fish consumption has been shown to alleviate vitamin D deficiency in populations in northern Europe during the winter months (O'Neill et al., 2016; Passarelli et al., 2024). Increased fish consumption may alleviate vitamin D, B12 and iron deficiencies in certain population groups such as children (NDNS, 2023) and elderly women (SACN, 2021), which will become more important when adopting dietary patterns with lower contributions from animal products, required to transition to low impact food systems (Payne et al., 2016). However, data was too scarce on these nutrients, with data being inconsistently presented in the literature between whole fish and edible portions on dry weight or wet weight basis, in order to provide an accurate nFIFO. This meant that a reliable model could not be produced. However, Löfstedt et al. (2025) mapped UK seafood supplies in relation to consumption and found that whilst oily fish supplies contribute to nearly half of the European recommended nutrient intake

(RNI) for LC n-3 PUFA, 34 % towards the RNI for vitamin B12, and 6 % for vitamin D, they only contributed minimally (e.g. less than 3 %) to calcium, zinc, vitamin A, and iron. This mapping was presented as a case study for high-income countries worldwide that have a high reliance on trade to keep fisheries and aquaculture profitable, but also to meet consumer demand and preferences. However, it must be acknowledged that percentage contributions to daily requirements will look different for coastal communities in tropical ecosystems, where populations are often more dependent on fish for the intake of a range of macro- and micronutrients (Zamborain-Mason et al., 2023). It should also be considered that most of these nutrients are not unique to aquatic (or specifically marine) systems and may be accumulated through other ingredients within aquafeeds or other components of the diet. However, the initial focus on LC n-3 PUFA as a key nutrient for validating the nFIFO is justified given its overall importance. We do highlight, however, that there is still incomplete understanding of the roles that other less well-known lipids, present in micro-quantities in fish oil, have on fish growth and physiology (Furse et al., 2024). This may offer further explanation to the limited effectiveness of plant-based fish oil alternatives to date and requires further research as part of efforts to optimize nutrient retention in aquaculture.

Our analysis currently does not distinguish between edible fish or portions of fish in or out, as demonstrated by previous research on farmed salmon (Willer et al., 2024). That is, it does not consider that within whole herring or mackerel being used as feed, only some of that input is edible. Nor does it consider that fish like sandeels are widely considered inedible. Similarly, the tool does not consider variation in the edible and inedible portions of the farmed fish out, or the nutrient content of salmon by-products. This would be the next logical step in the evolution of the tool but also adds another element of uncertainty, considering the differences in value of the co-products both nutritionally and economically. For the sake of simplicity and accessibility, we have chosen to present the tool on a whole fish basis, but we maintain that this level of detail is more than adequate for providing guidance on strategic use of marine ingredients and is a substantial improvement on the previous versions of FIFO.

5. Conclusion

The FIFO tool provides a simple metric to compare and aid in the improvement of marine ingredients utilisation. However, early versions have often led to skewed interpretations and misleading messages around efficiencies and environmental trade-offs in aquaculture production. The evolution to the nFIFO tool enables better management of key nutrition efficiencies that are a major consideration for fish and human health. However, better data resolution is required to improve accuracies and understand uncertainty in nutritional content, particularly of raw material supplies. The tool is provided as an Excel spreadsheet in the supporting information.

CRediT authorship contribution statement

Richard W. Newton: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wesley Malcorps:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation. **James P.W. Robinson:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Björn Kok:** Writing – review & editing, Validation, Methodology. **David C. Little:** Writing – review & editing, Validation, Investigation. **Anneli Lofstedt:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Baukje de Roos:** Writing – review & editing, Writing – original draft, Data curation. **David F. Willer:** Conceptualisation, validation, investigation, data curation, writing original draft, writing review and editing.

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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2025.742332.

Data availability

Data will be made available on request.

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