

Main challenges for measuring the sustainability of the marine ingredients industry: a systematic and critical review

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Abstract

The marine ingredients (MIs) industry is essential to the aquaculture sector, mainly providing fishmeal and fish oil to support animal feed and human nutrition. The exponential growth of aquaculture and the heavy reliance on finite marine resources pose significant sustainability challenges and highlight the need for more comprehensive and regionally adapted metrics beyond current Life Cycle Assessment (LCA) indicators and non-conventional LCA metrics.

In this systematic review, we analyzed 48 literature studies that focus on MIs sustainability using rigorous criteria for data quality and indicator relevance under the Prisma methodology. Our findings indicate that the studies that are mainly based on the LCA approach provide valuable insights into environmental performance, but are hindered by inconsistent metrics, limited data availability, and a lack of integration of economic, nutritional, and ethical dimensions in the sustainability analysis. Such limitations can lead to underestimate critical issues such as biodiversity loss, overfishing, and habitat degradation, while overemphasizing short-term efficiency measures, like feed conversion ratio, or environmental impacts such as global warming.

Additionally, emerging novel proteins and alternative uses for fish-derived byproducts, ranging from direct human consumption to high-value applications (bioactive compounds, cosmetic, etc.), to other low-value products (like biofertilizers), remains largely unexplored, given the absence of holistic and flexible assessment tools. Thus, the presence of unregulated contaminants (including additives, antibiotics and microplastics), are not yet adequately addressed in most MIs studies, despite some recent methodological advancements.

This review proposes the adoption of novel metrics, the standardization of assessment methods and the integration of multi-criteria decision analysis for LCA practitioners to better capture the complex and multifaceted challenges of MIs production, covering the way for more robust and reliable sustainability assessments within the aquaculture industry.

Keywords: *aquaculture; climate change; fishmeal and fish oil; FMFO; industrial ecology; Life Cycle Assessment.*

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63 **ACRONYMS**

ALCA	Attributional Life Cycle Assessment	FUI	Fuel use intensity
BPs	By-products	GHG	Greenhouse Gas
BRU	Biotic Resource Use	GW	Global Warming
CLCA	Consequential Life Cycle Assessment	IHC	Indirect human consumption
DHC	Direct human consumption	LCA	Life Cycle Assessment
Eu	Eutrophication	LCIA	Life Cycle Impact Assessment
FCR	Feed Conversion Ratio	LU	Land Use
FIFO	Fish-In: Fish-Out ratio	MIs	Marine ingredients
FM	Fishmeal	MPs	Microplastics
FMFO	Fishmeal and fish oil	POPs	Persistent organic pollutants
FO	Fish oil	SCP	Single cell protein
FU	Functional unit	WU	Water Use

64

65 **1. Introduction**

66 Increasing world population will inevitably imply an increase in the demand for high-quality
67 protein products in the coming years, challenging the global food industry. In fact, it is projected
68 that by 2050, demand for animal-based protein will double (Luthada-Raswiswi et al., 2021),
69 resulting in a 60-100% increase in food consumption for approximately 9.8 billion people (Ahmad
70 et al., 2022). In this context, seafood products are among the best-selling commodities in the
71 world, accounting for 17% of the animal protein consumed worldwide and 7% of total protein
72 consumption (FAO, 2020) and can constitute up to 50% of the average per capita intake of animal
73 protein (FAO, 2022a). The global seafood supply is made up of two interconnected sectors:
74 capture (or wild-caught) fisheries and aquaculture (or farmed fish) (Bjørndal et al., 2024). The
75 role of aquaculture has become particularly significant, and accounts since 2010 for over 50% of
76 the global fish food supply (Natale et al., 2013), even surpassing extractive fishing in world
77 production in 2023 (SOFIA, 2024), due to its profitability in the context of various factors,
78 including population and income growth (Bjørndal et al., 2024), producing over 400 aquatic
79 species, including ca. 200 species of fish, as well as mollusks, crustaceans, and algae (Tacon,
80 2019; FAO, 2022a).

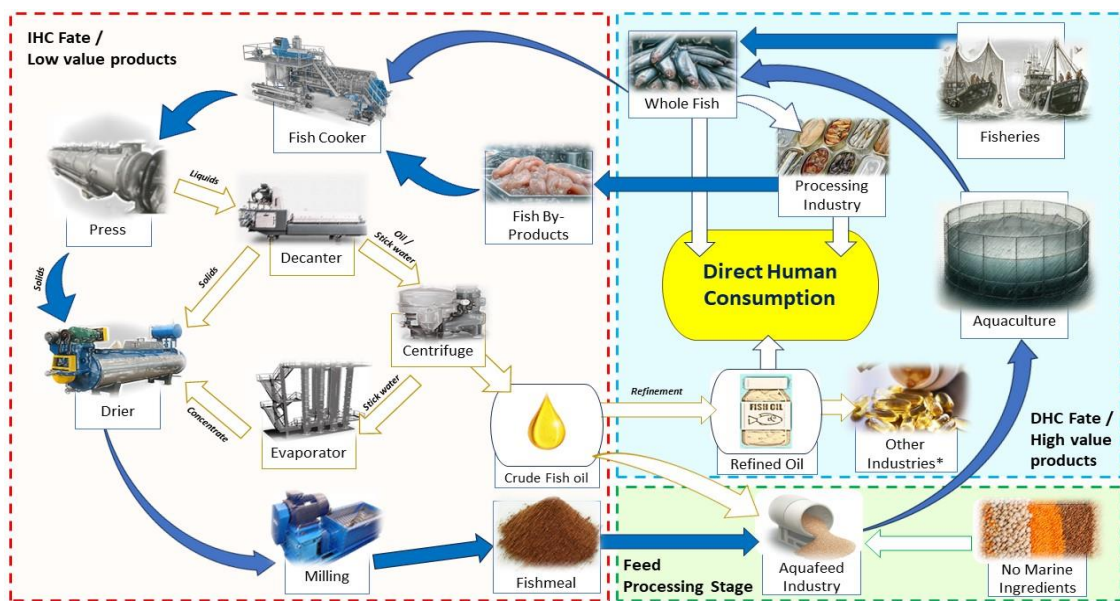
81 The marine ingredients (MIs) industry for aquaculture, mainly focused on the production of
82 fishmeal and fish oil (FMFO) from marine biomass, plays a critical role in this food production
83 system, especially in South America, Europe and Asia, providing essential nutrients and high-
84 quality proteins for seafood species (FAO, 2022a). Despite their importance, the production of
85 FMFO from MIs faces significant challenges, such as climate change and climate variability
86 impacts (Bjørndal et al., 2024; Brander, 2007), limited resources (Shepherd & Jackson, 2013;
87 Olsen & Hasan, 2012), and pressure on marine biodiversity (Naylor et al., 2009; Shannon &
88 Waller, 2021). Historically, Peru has been the world's largest producer, accounting for >20% of
89 fishmeal (FM) and ca. 15% of fish oil (FO) production in recent years, though several Asian
90 countries have recently shown exponential growth in FM production (EUMOFA, 2021; Olsen et
91 al., 2021).

92 Efficient FMFO production with modern technologies for fish reduction processes have been
93 widely adopted (Glencross et al., 2023), which includes cooking, pressing, drying, and milling
94 (Pelletier et al., 2018; Colombo et al., 2023). The reduction process (see Figure 1) results in a
95 brown dry powder rich in protein (Ahmad et al., 2022; Nagappan et al., 2021), which converts
96 one metric ton of forage fish (>65% of the total FMFO production from small fatty wild fish, such
97 as anchovies, sardines, mackerel, herring, etc.) into ca. 225 kg of FM and 50 kg of FO, although
98 quantities vary depending on the species and fat content in the raw material (Kok et al., 2020). A
99 significant portion (36%) of global marine capture fisheries' landings is used to produce FMFO
100 (Cashion et al., 2017; Natale et al., 2013), where Peruvian anchoveta (*Engraulis ringens*) is the

101 most important species in the global feed demand (Statista, 2022; IFFO, 2023) with a total catch
 102 of ca. 4,9 million tons (FAO, 2022a), although presenting semi-cyclical variations due to the
 103 effects of El Niño-Southern Oscillation – ENSO (Bertrand et al., 2020).

104 Aquaculture is the main consumer of FM (Olsen et al., 2021), as the primary source of animal
 105 protein in aquafeeds (Pelletier et al., 2018), used together with other vegetal proteins (like
 106 soybean). FM is used due to its high-quality protein content (Luthada-Raswiswi et al., 2021) and
 107 strict nutritional requirements for the growth and health of multiple species (Kok et al., 2020),
 108 like crustaceans (25% of total aquaculture production), or salmon and trout (15%) (EUMOFA,
 109 2021; IFFO, 2023). Most FM consumption in aquaculture is concentrated in Asia (69%), with
 110 China using 34%, and other Asian countries using the remaining 35% (IFFO, 2023).

111 FO is used in high-value sectors such as pharmaceuticals (Caldeira et al., 2020) and nutraceuticals
 112 (Olsen et al., 2021), cosmetics (Siahaan et al., 2022), bioactive compounds extractions (Hosseini
 113 et al., 2022), and applications in food products like bakery and pasta, due to their health benefits
 114 (Kadam & Prabhasankar, 2010). In any case, the current global demand for FMFO has driven in
 115 a high demand for feed resources and exceeds their global supply (FAO, 2022a).



116 **Figure 1.** Graphical representation of the main industrial processes from marine ingredients (MIs) The
 117 red dotted line delineates the steps involved in indirect human consumption (IHC) for fishmeal (FM) and
 118 fish oil (FO) processing. First, the raw material is cooked to denature the proteins and release the oil.
 119 Subsequently, the liquid is separated through pressing and used to produce FO. The solid residue is dried
 120 and crushed to produce a final fine powder. Both FM and FO are the result of the same production
 121 procedure. The blue dotted line illustrates the source of resource utilization for direct human consumption
 122 (DHC) as high-value products (*Other industries of refined oil use: pharmaceutical, cosmetic, petfood;
 123 etc.); The green dotted line encompasses the aquafeed processing steps derived from diverse ingredient
 124 origins. White arrows indicate the intended destination for DHC. Blue arrows indicate a potential
 125 destination for IHC. Yellow arrows indicate the fish oil cycle. Green arrows indicate the vegetal or non-
 126 marine material origin.
 127

128 Due to the limited availability of forage fish (Shannon & Waller, 2021), the demand of fish by-
129 products (BPs) by the feed industry is increasing (Naylor et al., 2009), along with the use of less
130 commercially viable fish species (Ordóñez-Del Pazo et al., 2014). Nevertheless, the growing
131 utilization of BPs does not necessarily indicate a reduction in the utilization of wild fish; rather,
132 it reflects an increasing demand for MIs (Majluf et al., 2024).

133 The use of fish BPs is around 33% of global FM production and 51% of FO production (FAO,
134 2018; Naylor et al., 2021). BPs are generated at various stages of seafood production, processing,
135 distribution, and disposal (Cooney et al., 2023), and represent important percentages of the whole
136 fish not used for DHC, such as skins and fins (1-3%), scales (5%), heads and bones (9-15%),
137 viscera (12-18%), and muscle trimmings (15-20%) (Luthada-Raswiswi et al., 2021), which can
138 constitute 50-70% of the total fish weight after industrial processing (Naseem et al., 2023).

139 The use of BPs presents a significant growth potential in Asia and China, with an estimated 36
140 million metric tons of feedstock available if all BPs are utilized (Jackson & Newton, 2016). From
141 an economic perspective, BPs are often used for activities that do not generate revenue, such as
142 waste, landfill (Nawaz et al., 2020) or incinerated (Thiele et al., 2021) or used to produce other
143 low-value products such as bioenergy or fertilizers through composting (Arvanitoyannis &
144 Kassaveti, 2008; Lopes et al., 2015). However, high-value added products like gelatins, fish
145 protein hydrolysates, and chondroitin sulfate can also be obtained (García-Santiago et al., 2021).

146 In addition to the measures mentioned above, there are concerns about reducing fishing pressure
147 on forage fish and marine ecosystems (Naylor et al., 2021) and the lack of effective fisheries
148 management for many stocks (Caldeira et al., 2020; Kok et al., 2020). This has led to the search
149 of alternative ingredients for aquafeed such as plant-based protein (e.g., soy, wheat, etc.)
150 (Konstantinidis et al., 2021), microorganisms (e.g., single cell protein (SCP) from fungi, bacteria,
151 microalgae, etc.) (McKuin et al., 2023; Hua et al., 2019), and insects (Sampathkumar et al., 2023).
152 These alternatives offer new opportunities to diversify and optimize feed sources for aquaculture
153 and other sectors, though they require careful and comprehensive evaluation regarding their
154 environmental and nutritional profiles.

155 **1.2 Key drivers of marine ingredients (MIs) demand: balancing nutrition and** 156 **sustainability**

157 The aquaculture industry relies significantly on the use of nutritional bases from a wide variety
158 of sources to meet the dietary requirements of farmed fish and crustaceans. MIs provide essential
159 proteins, omega-3 fatty acids (i.e., EPA and DHA), and vital micronutrients (vitamins and
160 minerals) that are necessary for optimal growth and health of aquaculture species (Luthada-
161 Raswiswi et al., 2021; Naseem et al., 2023). Although 70% of commercial fish production is
162 dependent on the use of non-natural ingredients in fish diet (terrestrial vegetal oils and grains),

163 MIs remain constant and recurrent type of feed used in aquafeeds, highlighting the critical role
164 that MIs play within this sector (Nagappan et al., 2021; Shannon & Waller, 2021).

165 The high nutritional value of forage fish could present a significant dilemma in the context of
166 their use for FMFO production versus direct human consumption (DHC). In countries like Peru,
167 anchoveta, a highly nutritious fish, is primarily employed for FMFO rather than addressing local
168 nutritional challenges (Majluf et al., 2017). This gives an indication of the potential issues that
169 may arise in terms of food security and accessibility, particularly in developing countries where
170 fish represents a significant source of animal protein for impoverished communities (Bjørndal et
171 al., 2024; Tacon & Metian, 2009), prioritizing the production of high-value exportable products
172 over local food security (Majluf et al., 2024). In fact, the competition between using forage fish
173 for aquaculture feed and for DHC may lead to food-feed competition, limiting the access to
174 essential nutrients for vulnerable populations (Alder et al., 2008). However, in the case of
175 Peruvian anchoveta, the lesser use of this fatty fish for DHC can be attributed to a wide range of
176 factors, including cultural barriers, food habits, limited availability of fresh fish in local markets
177 (Fréon et al., 2014), the lack of an appropriate and universal freezing supply chain throughout the
178 country, besides the economic interest that FM plants have developed through the decades in Perú
179 (Fréon et al., 2013).

180 From a sustainability perspective, the reliance on wild-caught forage fish for FMFO is
181 environmentally and ethically open to discussion. The overfishing of these stocks may represent
182 a significant threat to marine ecosystems and the biodiversity they support (Naylor et al., 2000;
183 FAO, 2022a). The environmental impacts are further evidenced by issues such as a decrease in
184 the ocean's capacity to produce fish, ocean acidification (negatively affecting mollusks) (Bjørndal
185 et al., 2024), bycatch, pollution from fishing operations, and the introduction of contaminants
186 such as heavy metals and microplastics into the food chain (Mo et al., 2018; Rummel et al., 2016).
187 Furthermore, the environmental impact of aquaculture is shaped by the production of feeds, which
188 provides origin to waste, chemical releases and ecological imbalances such as eutrophication
189 (Cole et al., 2009; Tovar et al., 2000). However, it is also true that forage fisheries, like anchoveta
190 in the Peruvian EEZ, represent one of the most efficient fuel intensity fisheries in the world
191 (Deville et al., 2025), due to their high catch rates, large-scale industrial operations (Fréon et al.,
192 2014), and energy-efficient fishing methods (Avadí et al., 2014).

193 The situation is further complicated by economic factors. The aquaculture sector is facing
194 pressure due to rising FMFO prices, which are the result of limited supply and increased demand
195 from high-value industries (Amer et al., 2019; Hua et al., 2019) and may drive up costs for end
196 consumers. The economic tension can intensify ethical challenges, as the redistribution of scarce
197 marine resources frequently benefits high-income consumers over disadvantaged communities,

198 influencing traditional diets and cultural practices (Fréon et al., 2014; Oirere, 2023). In fact, it is
199 estimated that a reduction in capture fisheries and slower growth in aquaculture over the next few
200 years will lead to a 52% increase in the price of commercial seafood, making fish much less
201 affordable and accessible (Bjørndal et al., 2024).

202 To address all these challenges for sustainable development, there is a persistent need to develop
203 and implement strategies that can balance the nutritional needs of aquaculture species with the
204 sustainability of marine resources and the accessibility of essential nutrients for human
205 populations. Therefore, the ongoing evolution of the aquaculture sector has required the
206 development of new metrics to accurately measure the use of MIs and a comprehensive set of
207 tools to assess the sustainability of this industry. However, sustainability and efficiency metrics
208 vary considerably between fishery, MIs production, and aquaculture practices. Moreover, despite
209 the important benefits of using these metrics, such as their ability to communicate the industry's
210 impact and transparently inform consumers, can be difficult to understand (Igos et al., 2019). In
211 fact, they can be complex and easily misunderstood because each area of activity has its own
212 unique priorities and environmental impacts, difficult to balance, and can lead to contrasting
213 conclusions (Silva et al., 2018) or to the use of the data for greenwashing purposes (Brandao et
214 al., 2024).

215 To address these concerns, the scientific community and decision-makers have proposed
216 environmental and sustainability indicators and certifications schemes to promote responsible
217 industrial practices in MIs industry. For instance, methodologies such as Life Cycle Assessment
218 (LCA) represents a small fraction of a wider range of sustainability management tools, but have
219 demonstrated they can provide a comprehensive and widespread analysis of environmental
220 impacts (Glencross et al., 2024), identifying and quantifying the carbon footprint, water use,
221 pollutant emissions, and other significant impacts from production to end-of-life of marine
222 resources (Ruiz-Salmón et al., 2021).

223 Based on ISO standards ISO 14040 and 14044 (ISO, 2006a, b), LCA is a widely used
224 methodology addressing sustainability issues in aquaculture (Bohnes et al., 2019). It serves as a
225 reference methodology for assessing the impacts of the supply chain and offers a global
226 perspective of the entire process/product life cycle (Hellweg & Canals, 2014). The LCA
227 framework, while essentially an environmental assessment mechanism, covers a series of
228 overlapping dimensions, including social, economic and nutritional impacts (Mclaren et al.,
229 2021), providing a holistic approach to sustainability assessment. However, despite important
230 advances in the methodology in recent years (Ruiz-Salmón et al., 2021), current LCA impact
231 pathways struggle to assess, in a comparable way, the full complexity of environmental
232 sustainability in aquafeed production (Bergman et al., 2025). Inadequate, biased, or incomplete

233 assessments can perpetuate unsustainable practices, increasing marine ecosystem degradation,
234 economic inequality, and global food insecurity. Consequently, in the ongoing effort to achieve a
235 balance between sustainability and global seafood consumption for a continually expanding
236 population, a critical question demands attention: How effective are the current metrics in the
237 sustainability Life Cycle Assessment of aquafeed production from marine ingredients?

238 Given these concerns, this systematic and critical review aims to comprehensively examine where
239 the current scientific literature, based mainly on LCA-oriented studies, provides suitable and
240 effective environmental indicators for MIs processing for aquaculture feed. The target audience
241 of this review is oriented to LCA practitioners, but the critical discussion derived from this review
242 is also useful to fisheries managers, academia interested in fisheries science and aquaculture
243 sectors, and stakeholders in the MIs industry to support decision-making for developing more
244 sustainable strategies in the industry.

245 **2. Methodology and data collection for the review**

246 A comprehensive literature review of peer-reviewed studies indexed in scientific journals was
247 conducted using the academic database Scopus (*www.scopus.com*), spanning a full decade from
248 2013 to 2023. The research focused on exploring assessment methods to evaluate the
249 sustainability of MIs, examining the FMFO processing and their utilization in the aquaculture
250 industry under a life cycle approach, as well as fishery BPs and alternative ingredient sources as
251 potential aquafeed substitutes. To compare the tools commonly used along the aquaculture value
252 chain, we conducted an evaluation of LCA-related and non-conventional LCA indicators for
253 sustainability assessment in the production of MIs, examining methodologies, system boundaries,
254 allocation perspectives and modeling approaches.

255 The methodology used was the Prisma systematic review process. With the intention of answering
256 the scientific question presented in the current review, a series of keyword combination were
257 selected, including “Fishmeal”, “Sustainability”, “Environmental”, “Indicators” and
258 “Assessment”. This preliminary search was not very fruitful in terms of the number of
259 publications (i.e., only 7 papers). Hence, a new series of combined searches were developed. The
260 combined concepts in following searches were: ““Fishmeal”, “Sustainability”, “Environmental”,
261 “Indicators”, “Assessment”, “Life cycle assessment” and “Animal feed”” in titles, abstracts, and
262 keywords (see Figure 2).

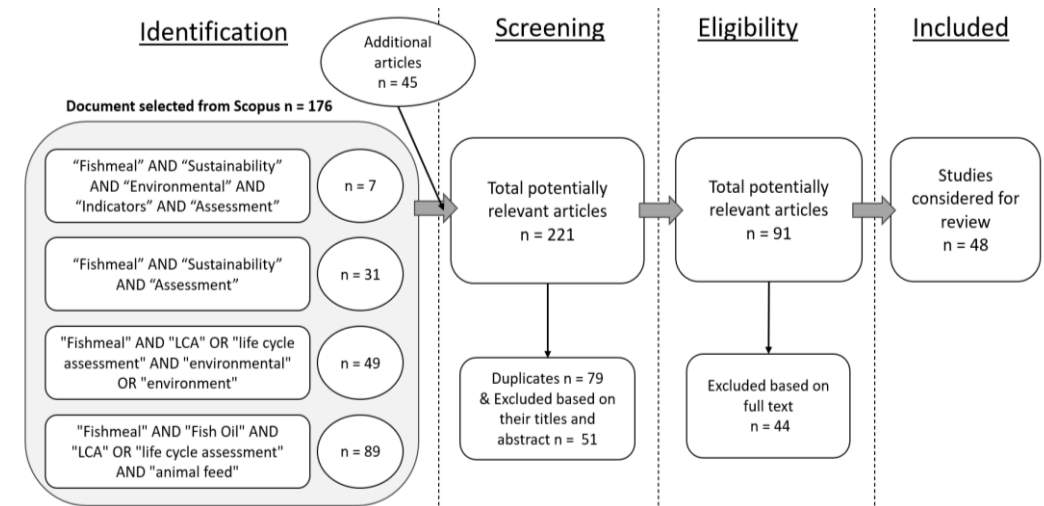


Figure 2. Flow chart of the selection process of studies for the systematic review.

Thereafter, the research involved the rigorous examination of titles and abstracts to identify relevant papers, followed by an in-depth analysis of reference lists and bibliographies within these articles to unearth additional suitable studies. The eligibility requirements included: i) the need for full length peer-reviewed articles; ii) the use of the English language; and, iii) focused on the environmental sustainability of aquaculture MIs, mainly in FMFO production assessment. Additionally, non-research materials, such as opinion papers, book chapters, conference proceedings, and grey literature, were excluded from the assessment. The management and organization of the full-text articles was handled using Mendeley reference manager provided by Elsevier Inc. (www.Mendeley.com).

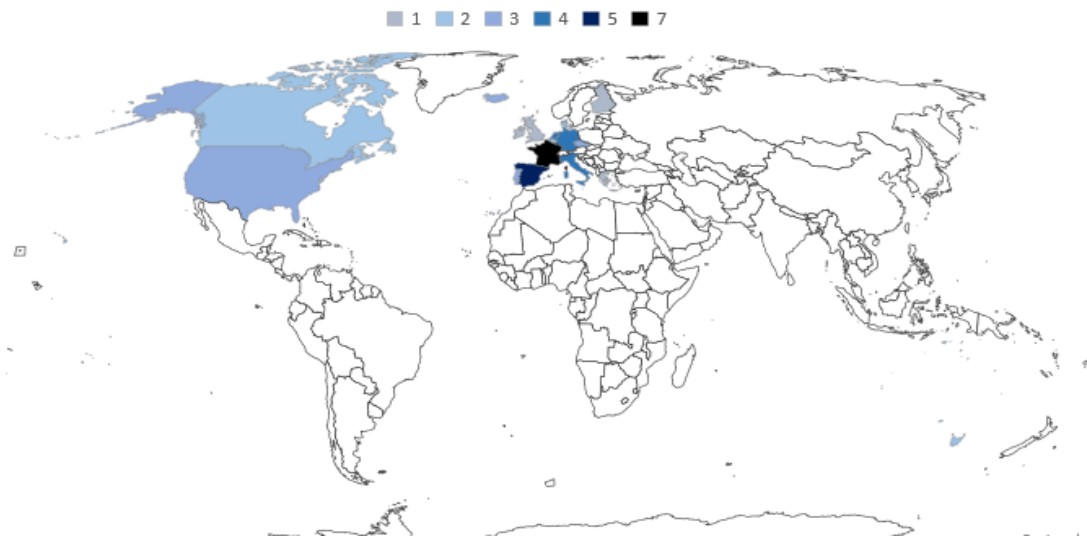
From the initial search, a total of 221 potentially relevant articles were identified (176 articles in Scopus and 45 additional articles identified through other alternative sources). After removing 79 duplicate entries, 95 articles that did not address the research question were excluded following a review of their titles, abstracts, and full text examination. This resulted in 48 articles being selected for a detailed analysis, as they met all the requirements proposed. These articles were subsequently included in the final systematic review and critical analysis.

3. Results

3.1 Mapping, time evolution and sources of the studies selected

In the field of scientific research, the geographical distribution of studies provides a crucial perspective on the predominant trends and approaches in different regions. A total of 17 countries were identified based on this criterion, evidencing a significant lack of contributions from Asian and South American countries, despite being the main producers of MIs worldwide. This observation is particularly noteworthy given the importance of Asia in the global MIs industry, not only in terms of production, but also regarding consumption and imports. Figure 3 illustrates

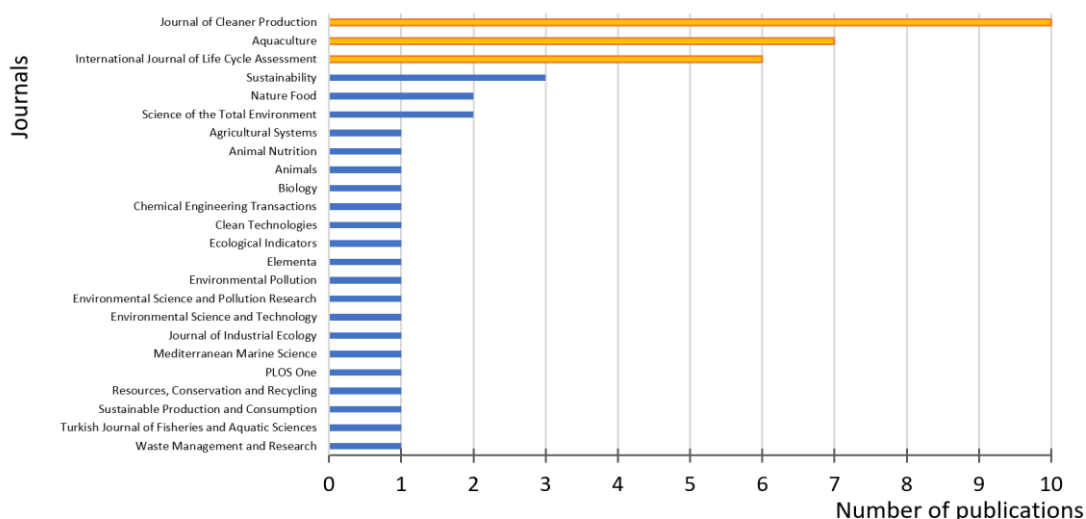
288 the geographical distribution of the studies, with France emerging as the leader (7 studies), Spain
289 (5), and The Netherlands, Italy, and Germany (4 studies each).



290 **Figure 3.** Geographic distribution of marine ingredients sustainability related studies included in the
291 review. Increasing color intensity indicates a higher count in the number of studies included in the review
292 performed. To establish geographical classification, the first author's affiliation has been identified as a
293 key criterion for consideration.
294
295

296 Overall, Europe has the highest concentration of research (i.e., 37 studies). This dominance may
297 be influenced by various factors, such as the availability of research funding (e.g., Beyers et al.,
298 2023; Maiolo et al., 2021), specialized academic and research centers in MIs sustainability (e.g.,
299 Henriksson et al., 2015; Newton et al., 2023), and greater public and political awareness regarding
300 sustainability issues (e.g., Mungkung et al., 2013; Avadí et al., 2015). Although the classification
301 based on first author affiliation provides a useful overview, it also has limitations, as some studies
302 are compilations of research conducted by other authors, or the affiliation does not always equate
303 to the region of interest under assessment. This result underscores the importance of achieving a
304 more balanced and global understanding of the challenges and solutions in the field of
305 sustainability in the MIs industry. Hence, it is essential to foster international collaboration and
306 knowledge sharing, including studies from different regions, particularly Asia.

307 The selection of journals for publication reflects trends in knowledge dissemination and
308 researchers' preferences for visibility and impact (see Figure 4). From the studies analyzed, three
309 scientific journals stand out for the number of publications related to this field: "Journal of Cleaner
310 Production", "Aquaculture", and "The International Journal of Life Cycle Assessment",
311 accounting for almost half of the total number of publications used in this review (i.e., 23 of 48
312 articles). In contrast, the remaining journals used in the studies reviewed do not show a significant
313 concentration of articles, suggesting that the interdisciplinary nature of MIs-related research
314 provides multiple platforms where studies on these topics can be published.



315

316 **Figure 4.** Distribution of the 48 publications examined in the current marine ingredients' sustainability
 317 assessment review in scientific research journals. All publications were published within the 2013-2023
 318 timeframe. Results are presented from highest to lowest number of publications in each journal, with the
 319 orange bars representing the journals that had the highest number of articles on the topic evaluated.

320 3.2 Scientific contributions to fishmeal and fish oil processing assessment

321 Most of the publications reviewed describe the considerable amount of whole forage fish currently
 322 used in the MIs industry. However, only a few studies directly address the processing of forage
 323 fish into FM and its impact on the ecosystem, as well as other associated environmental impacts.
 324 In fact, for this review, only 3 studies dealt with complete data directly obtained from FMFO
 325 production. These studies include: i) Fréon et al. (2017), which base their assessment on the
 326 production of FM from three different types of Peruvian reduction plants; ii) Hilmarsdóttir et al.
 327 (2022), who focus on the production of an FMFO plant that uses capelin, a blend of mackerel and
 328 herring cut-offs, and blue whiting; and, iii) Silva et al. (2018), who discuss the processing of BPs
 329 in a Portuguese company. Other studies based on FM production from fish BPs focus mainly on
 330 valorizing waste from the canning industry, such as European anchovy (Laso et al., 2016) and
 331 skipjack tuna (Cortés et al., 2021), but provide limited data on FM inputs and outputs. Newton et
 332 al. (2023) compile LCA-based inventories of FMFO, mainly based on fishery inventories
 333 published, such as studies on anchoveta rendering (Fréon et al., 2017), the Danish LCA food
 334 database (<https://lcafood.dk>) or a brief FMFO mass balance of the canned tuna industry (Cortés
 335 et al., 2021).

336 The remaining studies in this review evaluate the impact of MIs on aquaculture diets compared
 337 to alternative ingredients, using data obtained from external sources such as AgriBalyse
 338 (Konstantinidis et al., 2021; Maiolo et al., 2020; Wilfart et al., 2023), Agrifootprint (Bordignon et
 339 al., 2023; Parker, 2018), ecoinvent (Roffeis et al., 2020; Samuel-Fitwi et al., 2013) or adapted
 340 from ecoinvent (Beyers et al., 2023; McKuin et al., 2023), and Gabi (Couture et al., 2019; Laso
 341 et al., 2016; Togarcheti & Padamati, 2021), among others.

342 4. Current approaches to assess sustainability in the marine ingredients 343 processing industry

344 4.1 Methodological choices in LCA systems

345 4.1.1 Scope

346 Our review identified 34 documents related to LCA, but less than one-third (12) addressed whole
347 fish or fish BPs processing to MI. The selected studies in the review often compare the
348 environmental performance of feeds by assessing their use in diets relative to alternative protein
349 sources for aquafeeds, ranging from marine microalgae (McKuin et al., 2023), to terrestrial BPs
350 like poultry meal (Campos et al., 2020). This limited focus in MIs processing may stem from
351 various challenges, including a lack of data, transparency (Bohnes & Laurent, 2021; Fréon et al.,
352 2017) and difficulties retrieving available FM rendering data (Newton et al., 2023).

353 Some of these data gaps and different methodological approaches have promoted efforts to
354 standardize criteria for feed ingredient datasets. An example of these efforts is the case of the
355 solution proposed by Global Feed LCA Institute (GFLI). GFLI (globalfeedlca.org) has developed
356 a publicly accessible database with over 1800 Life Cycle Assessment (LCA) datasets, which have
357 been aligned with international standards such as FAO-LEAP and EU PEFCR Feed (Fritter et al.,
358 2020), that helps to improve consistency, credibility, and transparency in the feed sector database.
359 However, some challenges need to be solved.

360 For example, some authors also point out that market price fluctuations can make it difficult,
361 including economic data in MIs LCA studies (Silva et al., 2018). The real issue with these price
362 fluctuations is that they can lead to inconsistent or outdated results, which may mean that
363 achieving accurate results requires more work in model development but is not in itself a barrier
364 to including MIs in the analysis (Deville et al., 2025). Likewise, LCA often excludes construction
365 and maintenance of infrastructures for FMFO processing and other activities related to MIs
366 manufacturing, which can result in an incomplete assessment of these processes (Fréon et al.,
367 2018). The need to standardize scope criteria shall be fundamental to making comparative studies
368 in MIs industry, including the origin of raw materials, the industry infrastructure and maintenance
369 data and the final fate of the final products developed from MIs.

370 4.1.2 Functional unit, system boundaries and Life Cycle Inventory

371 The LCA literature commonly uses one metric ton of fish caught as the functional unit (FU) to
372 quantify environmental impacts in aquaculture-related studies (Konstantinidis et al., 2021).
373 However, other reference units were also identified. In particular, the standard FU of measurement
374 often focused on production or supply of the seafood industry, such as landed anchoveta (Avadí
375 et al., 2014), raw tuna at the processing plant (Cortés et al., 2021), or anchovy for the canning
376 industry (Laso et al., 2018). Similarly, in aquaculture, the FU is frequently defined by the weight

377 of fresh farmed fish (Avadí et al., 2015; Bosma et al., 2011) or fresh fish delivered to the market
378 (Konstantinidis et al., 2021). Notably, when fresh fish delivered to the market serves as the FU, it
379 becomes possible to assess the farm to fork impact, by incorporating transportation and
380 refrigeration chain factors.

381 Beyond mass-based measures, some LCA choose more focused aquafeed-related FU, such as “1
382 t of fishmeal and fish oil” (Hilmarsdóttir et al., 2022) or “1 kg of pellets” (Goyal et al., 2021).
383 While this type of FU can facilitate feed-based comparison, they may become misleading in cross-
384 species analyses, due to variation in nutritional requirements (Wilfart et al., 2023), productions
385 systems (Henriksson et al., 2015), energy sources (Fréon et al., 2017), and regional context
386 (Newton et al., 2023) under different environmental indicators.

387 To address these limitations, alternative FUs such as “1 kg microalga” or 1 “kg as meal”
388 (Penaranda et al., 2023) represent less conventional yet resource-efficient strategies for
389 aquaculture development. However, if real yield or nutritional benefits are not fully captured,
390 these FU risk underestimating the advantages of certain aquaculture practices or product (Samuel-
391 Fitwi et al., 2013). For instance, Wilfart et al. (2023), adopt “1 kg of body weight gain” to consider
392 actual growth outcomes more effectively.

393 Some assessments shift the focus towards nutritional aspects or components relevant to human
394 health, for example “1 kg of EPA+DHA” (Togarcheti & Padamati, 2021), “1 kg of edible seafood”
395 (Bohnes & Laurent, 2021), “1 t of protein content” (Maiolo et al., 2020), or “1 kg of crude protein”
396 (McKuin et al., 2023). This approach reflects the growing importance on nutritional quality in
397 LCA studies of agri-food systems (Mcauliffe et al., 2020). As demonstrated by Sonesson et al.
398 (2019) and Jolliet et al. (2022), considering dietary context can significantly modify perceptions
399 of environmental performance, highlighting the need to integrate nutrition into LCA analyses.

400 Focusing solely on mass-based FU may omit the broader functionalities of seafood (Deville et al.,
401 2025), and lead to an incorrect comparison of environmental impacts, especially among different
402 protein alternatives. This limited perspective can result in an incomplete understanding of the
403 overall environmental impact. Such an approach can produce an incomplete picture of overall
404 sustainability. Moreover, factors, such as local communities’ welfare, labor conditions, and
405 regional economic impact (often overlooked in LCA), can shape how FUs are selected, especially
406 considering that Life Cycle Sustainability Assessment (LCSA) studies are proliferating in the
407 scientific literature (Larsen et al., 2022).

408 **4.1.3 Allocation perspectives**

409 Discussions on the most effective allocation approaches for accurately reflecting the sustainability
410 of MIs tend to be particularly dynamic compared to other production systems (Pelletier &

411 Tyedmers, 2011). In fact, allocation choice is complex because it can heavily influence study
412 outcomes (Svanes et al., 2011), making comparisons even among similar products inherently
413 challenging (Goyal et al., 2021). According to the reviewed studies, the most used allocation
414 methods were mass (55%), and economic (52%), followed by energy allocation (21%). In general,
415 there are two main types of allocation in LCA studies: economic and biophysical (e.g., mass or
416 energy), approaches that can sometimes be seen as antagonistic. The main difference lies in how
417 they distribute impacts (Svanes et al., 2011), but no single method is the best allocation for every
418 situation (Ardente & Cellura, 2012).

419 Economic allocation usually assigns environmental burdens based on the economic value of
420 products but is susceptible to market fluctuations, leading to distortions in highly volatile markets
421 (Deville et al., 2025). For instance, Pelletier & Tyedmers (2011) warn against relying heavily on
422 market data for LCA, particularly through economic allocation, arguing that it introduces
423 distorted view of environmental dimensions of economic activities from a biophysical
424 perspective. Relying solely on market indicators for a product can undermine the method value
425 of LCA in promoting eco-efficiency and sustainability, ignoring the broader macroecological
426 dimensions of material and energy flows (Pelletier & Tyedmers, 2011). Not surprisingly, the ISO
427 14044 standard advises using economic allocation only when other methods are not appropriate
428 (Ardente & Cellura, 2012).

429 In contrast, biophysical allocation (mass or energy based) tends to offer more stable outcomes.
430 However, it may overlook economic value, which can be important for some policymaking and
431 market considerations. In terms of MIs, multiple studies highlight the advantages of mass
432 allocation: Smáráson et al. (2017) suggest that mass allocation promotes stability and circularity
433 of BPs in aquaculture, while Basto-Silva et al. (2019) and Silva et al. (2018) identify it as the most
434 suitable co-product allocation in the aquafeed industry. Indeed, biophysical approaches often shift
435 more environmental burden to feed systems compared to economic or no-impact allocation
436 (Parker et al., 2018). However, not all FMFO are produced from BPs, such as Peruvian anchoveta.
437 Avadí et al. (2014) found energy allocation to be more stable, because fat content can boost FO
438 production, while FM yields relatively constant (Deville et al., 2025). Consequently, researchers
439 consider allocation based on physical properties better aligned with understanding and managing
440 the environmental footprint of products satisfying human needs (Pelletier & Tyedmers, 2011).

441 In addition to these opinions, the best practices guidelines in LCA often recommend conduct
442 sensitivity analyses with multiple allocation methods. This pathway was identified for 30% of the
443 studies assessed in this review. This allows understanding how results may be affected by different
444 allocation choices in the same process/product. Incorporating different allocation systems within
445 a single LCA can thus enhance result robustness, uncover key factors influencing overall impacts,

446 and support better-informed decisions regarding MIs sustainability. By preventing misleading
447 dissemination or greenwashing, this approach helps stakeholders gain more accurate, credible
448 understanding of MIs true environmental performance (Brandao et al., 2024).

449 4.1.4 Modelling approaches

450 Almost all the LCA studies examining the sustainability of MIs adopt an attributional LCA
451 (ALCA) perspective (97%). ALCA aligns with general LCA trends by distributing environmental
452 burdens directly (Finnveden et al., 2009), offering less complex modelling (Brander et al., 2019),
453 and relying heavily on precise, comprehensive, and up-to-date datasets (i.e., retrospective or
454 steady-state), particularly regarding fish populations and fishing methods (Vázquez-Rowe &
455 Benetto, 2014), than consequential LCA (CLCA).

456 By contrast, CLCA (found in 9% of reviewed LCA studies), offers a more expansive perspective
457 than ALCA approach, as it analyzes the potential impacts on policy changes or strategic decisions
458 on other production systems, and often tries to combine economic models with environmental
459 assessments (Rege et al., 2015). However, this added scope can increase complexity and
460 introduces uncertainties, give the challenges of defining clear boundaries (Vázquez-Rowe &
461 Benetto, 2014) and forecasting the dynamic changes within the markets in which the final
462 products are traded (Suh and Yang, 2014).

463 Within the MIs sector, some authors, such as Samuel-Fitwi et al. (2013), argue that CLCA is the
464 most suitable method for assessing aquaculture-related food impacts. Proponents of CLCA claim
465 that substituting one product for an alternative also substitutes its environmental impact for that
466 the original product under analysis (Parker et al., 2018), while Wilfart et al. (2023) state that
467 CLCA predicts the potential future effects of changing demand. In this sense, the only exclusively
468 CLCA-based study in this review is Beyers et al. (2023), which analyzes black soldier fly larvae
469 as an alternative protein source for feed in aquaculture diets.

470 Some studies advocate a combined approach, using both ALCA and CLCA to fulfill different
471 objectives (Bordignon et al., 2023; Brander et al., 2019 and Samuel-Fitwi et al., 2013). For
472 instance, Samuel-Fitwi et al. (2013) assess standard trout feeds using both ALCA and CLCA, then
473 apply CLCA to feeds substituted with canola meal and soybean meal to capture the indirect
474 impacts of aquaculture feed production more effectively. While CLCA can provide detailed
475 insights into how various decisions influences outcomes, ALCA focuses on a product's
476 contribution to the overall environmental impact without considering the consequences of future
477 decisions (Ekvall, 2019). This characteristic makes ALCA particularly valuable for carbon
478 footprint analysis, certification and environmental product declarations (Majeau-Bettez et al.,
479 2018). Looking forward, however, greater reliance on CLCA for MIs could clarify the
480 consequences of changing feed ingredient in aquafeed diets. In the meantime, the choice between

481 ALCA and CLCA will therefore depend on the specific goals of the study and the decision-making
482 context.

483 In addition, hybrid LCA methods, which integrate process-based and input-output data, have been
484 introduced in both the food industry and construction sectors to address some limitations of
485 traditional LCAs (Li et al., 2020). By integrating economic and environmental data, these hybrid
486 approaches offer more comprehensive impact assessments, can provide deeper and more accurate
487 evaluations of environmental and socioeconomic factors, and facilitate the identification of
488 improvement opportunities to promote sustainable and responsible practices within the aquafeed
489 industry. Ongoing development of methods to prevent double counting in hybrid LCAs, helps to
490 ensure accuracy when harmonizing process-based and input-output data (Agez et al., 2020).

491 Finally, it should be noted that current database developments also allow for the development of
492 ex ante or prospective LCA studies, which allow applying an attributional LCA perspective to
493 emerging or future technologies (de Souza et al., 2023). However, we did not identify any of these
494 studies applied to aquafeeds in the period analyzed.

495 **4.1.5 Life Cycle Impact Assessment**

496 The most frequently used Life Cycle Impact Assessment (LCIA) method identified in the 35
497 LCA-based studies covered in this review are the ReCiPe method (48%) and CML (40%). CML
498 has gained widespread use in LCA research owing to its comprehensive approach to classifying
499 and characterizing environmental impacts. It is widely used in aquaculture (Smáráson et al., 2017)
500 and other sectors like agriculture (Alhashim et al., 2021), due to its early development as one of
501 the first holistic methods available in literature, which ensure compatibility with a variety of
502 livestock and food production studies.

503 Despite their prevalence, both ReCiPe and CML methods have notable limitations when it comes
504 to marine-related indicators. Couture et al. (2019) and Roffeis et al. (2020) identified that these
505 methods often fail to account for impacts directly related to biotic resource use, seabed impact
506 and other marine-specific factors. Similarly, Laso et al. (2018) underscore the uncertainty that the
507 ReCiPe endpoint methodology can introduce, given that different approaches may affect final
508 decision-making processes. Nonetheless, the ReCiPe egalitarian perspective can be considered
509 more precautionary, selected by Fréon et al., (2017) to adopt it standardizing the MIs production
510 assessment in Peru.

511 In response to these shortcomings, some studies mitigate potential gaps by using multiple
512 complementary LCIA methods. For example, Laso et al. (2018) combine categories from IPCC
513 2013, CML/IA, and ReCiPe endpoint method, to evaluate anchovy BPs. Similarly, Parker et al.
514 (2018) employ both ReCiPe method and CML-IA Baseline to investigate the use of fish BPs in

515 aquaculture feeds, and Bohnes & Laurent (2021) examine the substitution of FMFO from whole
516 fish by fish trimmings and insects using a mix of IPCC, CML-IA, IMPACT World+, USEtox, and
517 AWARE. However, Bohnes et al., (2019) caution that this heterogeneous application of different
518 methodologies can poses challenges related to methodological uniformity, reliability and overall
519 scientific robustness.

520 Although many studies rely on ReCiPe or CML, a smaller portion use different methods,
521 including IMPACT+ (Bohnes & Laurent, 2021; Ferronato et al., 2023; Van Phi et al., 2020), or
522 the IPCC method solely for GHG emissions (Laso et al., 2018; Bohnes & Laurent, 2021; Van
523 Zanten et al., 2015). More recently, Beyers et al. (2023) employed the Environmental Footprint
524 (EF) methodology, promoted by the European Commission. Furthermore, in October 2024, the
525 Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM) project
526 (<https://www.lifecycleinitiative.org/category/glam/>), promoted by the Life Cycle Initiative,
527 launched the GLAM method, informed by extensive scientific collaboration worldwide. This new
528 approach includes an additional marine-related indicators that capture climate effects on various
529 aquatic ecosystems, water use impact factors based on species-discharge relationships, macro-
530 and microplastic pollution in the marine environment (Hajjar et al., 2024) and the quantification
531 of fish biomass removal (Stanford-Clark et al., 2024), essential factors when assessing MIs
532 sustainability.

533 Despite these advancements, most current environmental impact indicators were initially
534 developed for terrestrial and freshwater ecosystems and fail to address key drivers of marine
535 biodiversity loss (Woods et al., 2016). Promisingly, recent studies have begun exploring seabed
536 impact (Woods and Verones, 2019), targeted resources depletion (Stanford-Clark et al., 2024;
537 Hélias et al., 2023), and methods to quantify the damage from plastic pollution (Casagrande et
538 al., 2022; Hajjar et al., 2024; Lavoie et al., 2022;). Updates like Impact World v2.1 (December
539 2024) reflect these emerging concerns by adding new marine-related impact categories, such as
540 fisheries depletion (based on Stanford-Clark et al. (2024)), microplastics and marine toxicity. In
541 this sense, it is expected that a new generation of publications linked to MIs will incorporate some
542 of these methods.

543 Nevertheless, accurately capturing marine biodiversity impacts in LCIA remains highly complex,
544 encompassing genetic, species and ecosystem-level diversity (Lindner et al., 2019), and a
545 taxonomic breadth (Verones et al., 2015), and they are not fully equipped to predict how diverse
546 species and ecosystems will respond to environmental changes (Winter et al., 2017).

Table 1. Summary of main characteristics of the reviewed Life Cycle Assessment (LCA) studies include the perspective (i.e., attributional or consequential), Life Cycle Impact Assessment (LCIA) method, allocations, functional unit, and topic.

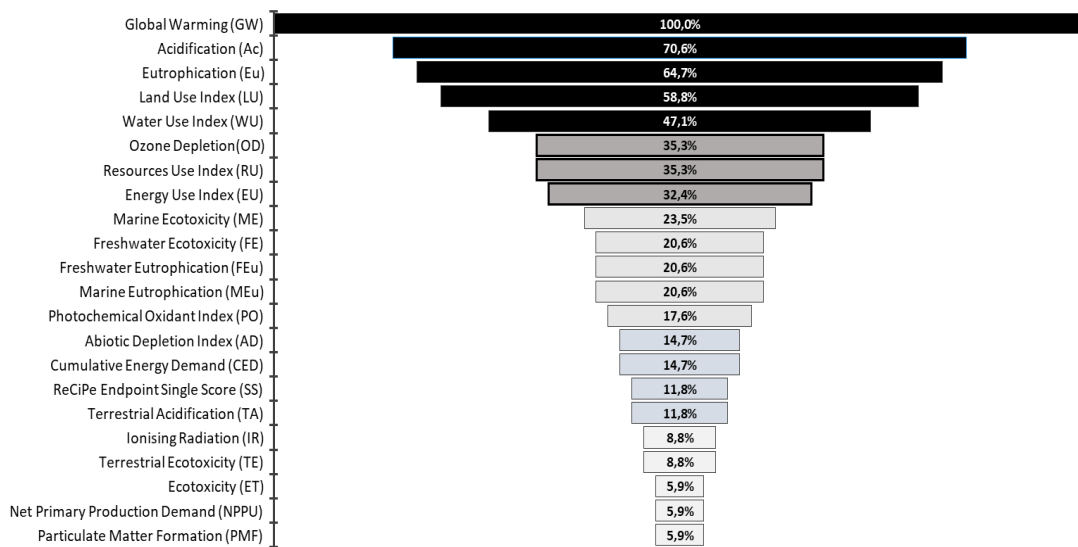
Authors	Perspective	LCIA Method	Allocation	FU	Topic
MIs PROCESSING/ BPs PROCESSING AND VALORIZATION TO MIs					
Avadí et al., 2014	ALCA	ReCiPe/ CMLb1 2000/CED/USEtox	N/A	1 t of landed anchoveta	Assessment of DHC vs IHC of Peruvian anchoveta
Avadí et al., 2015	ALCA	CML 2 / ReCIPE	Mass-GEC	1 t live weight, fresh farmed fish	Comparison of commercial versus artisanal feeds in Peruvian freshwater aquaculture
Cortés et al., 2021	ALCA	Recipe 2016	Economic	1 t of raw tuna at processing plant gate	Multiproduct strategic in tuna can industry study
Fréon et al., 2017	ALCA	ReCiPe	Mass/Economic	1 t output-based & process-based FM	FM Processing LCA
García-Santiago et al., 2021	ALCA	ReCiPe Midpoint (H) method	Mass	100 kg of whole cartilaginous fish	Marine biorefinery for valorization versus conventional MIs
Hilmarsdóttir et al., 2022	ALCA	ReCiPe 2016	Energy	1 t fishmeal and fish oil	Study of MIs production plant in Iceland; Raw material acquisition and processing
Laso et al., 201 ^a	ALCA	iCheme, 2002	N/A	1 can of final product	LCA study to identify BAT in the anchovy canning sector
Laso et al., 2016b	ALCA	iCheme, 2002	Economic	1 t of anchovy wastes	LCA study on canning factory anchovy process with MIs production
Laso et al., 2018	ALCA	IPCC 2013 / CML/ ReCIPE	N/A	1 kg of anchovy	Anchovy-based products for IHC (FM) and for direct human consumption
Newton et al., 2023	ALCA	CML Baseline	Mass/Economic	1 t MI produced	Evaluation of MI process efficiency
Silva et al., 2018	ALCA	CML-IA baseline V3.04	Mass	1 t of ingredient used	FM substitution in feed: sardine and tuna fish and Peruvian anchovy
Togarcheti et al., 2021	ALCA	CML	Mass	1 kg EPA+DHA	Evaluation of FO extraction methodologies
MIs ASSESSMENT IN FEEDS/DIETS					
Basto-Silva et al., 2019	ALCA	Recipe	Mass	1 kg of experimental diet	Experimental diets replacement of MIs
Beyers et al., 2023	CLCA	Environmental Footprint 3.0	Economic	1 t protein in livestock feed	Diet comparison with conventional MIs use
Bohnes & Laurent, 2021	ALCA.	IPCC; CML-IA; IMPACT World+; USEtox; AWR	Mass/Economic	1 t of edible seafood	Assess the conventional MIs ingredient substitution with trimmings or insects
Bordignon et al., 2023	A/CLCA	CML-IA method	N/A	1 kg of diet production	Study of diets with substitution of FO alternatives
Bosma et al., 2011	ALCA	ReCiPe-2008/ CML2	Mass	1 ton of fresh fish	Environmental impacts in the production of striped catfish in intensive farming systems
Campos et al., 2020	ALCA	CML	Economic	1 t of ingredient to fish feed producer	Compare different feedstuff for aquaculture vs MIs, replacing FO and FM.
Couture et al., 2019	ALCA	ReCiPe	Economic	1 kg of feed	Evaluation of use of SCP for Feeds Analysis
Ferronato et al., 2023	ALCA	IMPACT 2002+	N/A	1 t of OFMSW	FM substitution for alternative ingredients
Goyal et al., 2021	ALCA	ReCiPe 2016	Mass	1 kg LH pellets	Study of diet substitution of conventional FM with insects
Konstantinidis et al., 2021	ALCA	ReCiPe 2016	Mass/Energy	1 t of harvested fish	Comparing diets: identify environmental hotspots linked to fish feeds granulations
Maiolo et al., 2020	ALCA	CML-IA method	Mas/Economic	1 t of protein content	Assessment of 4 partial FM substitutes in diets formulation of new aquafeeds
McKuin et al., 2023	ALCA	ReCiPe 2016;	Economic	1 kg crude protein	Study of diets with alternative ingredients for FM substitution
Mungkung et al., 2013	ALCA	CML2 Baseline 2000 method	Mass/Economic/Energy	1 t of fresh fish delivered to the market	Diets in environmental impacts associated with two-net cage aquaculture systems
Nhu et al., 2016	ALCA	RECIPE; Natural Environment (CEENE)	Mass/Economic/Exergy	1 t live weight of Pangasius	Comparison between Pangasius produced on ASC farm & non-ASC intensive farms
Parker, 2018	ALCA.	ReCiPe method / CML-IA Baseline	Mass/Economic/Energy	1 kg of head-on gutted (HOG) salmon	Use of animal by-product inputs in aquaculture feeds
Penaranda et al., 2023	ALCA	Environmental footprint (EF) / CED	Economic	1 kg microalgae & 1 kg meal as feed.	Algae meal was compared with fishmeal for feed uses
Roffeis et al., 2020	ALCA	ReCiPe	Economic	1 kg IBM	Comparison of Insect based diet versus conventional FM in fish
Samuel-Fitwi et al., 2013	A/CLCA	CML 2000	Mass	1 t of rainbow trout feed	Trout diet assessment by different formulation
Smáráson et al., 2017	ALCA	CML 2 Baseline 2000 / CED	Mass	1 kg of live-weight Arctic char	Experimental diets replacement (conventional meal vs vegetal meal vs insect meal)
Van Phl et al., 2020	ALCA	IMPACT 2002+	Economic	1 t of IM equivalent to 1.03 t of FM	Compare Insect Meal versus conventional Fishmeal
Van Zanten et al., 2015	ALCA	IPCC	Economic	1 t larvae meal on dry matter basis	Evaluation of ingredient substitution in livestock feed
Wilfart et al., 2023	ALCA	ILCD / CML	N/A	1 kg of body-weight gain	Assessment of Feed formulas; Feed digestibility; Growth performance in fish
Wind et al., 2022	ALCA	CML-IA baseline	Mass/Energy	1 kg fish live weight	Comparison of plant-based vs fish-based feed diet

DHC: direct human consumption; IHC: indirect human consumption; GEC: Gross Energy Content; BAT: best available techniques; FM: fishmeal; FO: fish oil; MIs: fishmeal/fish oil; SCP: single cell protein; OFMSW: organic fraction of municipal solid waste; LH: combination of *Lemma minor* and *Hermetia illucens* meal; IBM: insect base meal; IM: insect meal; LCA: life cycle assessment; ALCA: Attributional LCA; CLCA: Consequential LCA.

550 **4.2 Commonly analyzed environmental impacts of marine ingredients (MIs) in LCA**

551 The studies reviewed show considerable variability in how impact categories are analyzed. Global
 552 Warming (GW) or equivalent indicators dominate the most used categories, accounting for 100%
 553 of the LCA-based studies (see Figure 5). The second most frequently used category is
 554 acidification (Ac), included in 71% of the LCA-related publications, followed by eutrophication
 555 (Eu) in 65%, land use (LU) in 59%, and water use (WU) in 47%. Notably, LU metrics generally
 556 consider only terrestrial land occupation or transformation, whereas seabed-specific metrics, such
 557 as the Woods and Verones (2019) method, are largely unexplored.

558 A second set of impact categories encompasses ozone layer depletion (OD) and resource use
 559 (RU), both featuring in 35% of the studies, and energy use (EU) in 32%. The relatively low use
 560 of OD may be explained by the decrease in the emissions of ozone-depleting substances in recent
 561 decades, although many fishing vessels still employ these substances as cooling agents, one of
 562 the current primary sources of such emissions (Rusch, 2018). Meanwhile, RU has begun to evolve
 563 by incorporating advanced impact pathways that account for the criticality and circularity of
 564 resource intensive products (Schulze et al., 2020a, b).



565 **Figure 5.** Main environmental impact indicators used in Marine Ingredients (MIs), mainly fishmeal and
 566 fish oil, sustainability assessment. Each horizontal bar represents a different indicator, and the length of
 567 the bar indicates the percentage of the rating that indicator represents in the number of times used in the
 568 publication of the review.
 569

570 Freshwater (FE) and marine (ME) ecotoxicity, along with marine-specific indicators, such as
 571 stock depletion or net primary productivity demand, photochemical oxidant (PO) and Abiotic
 572 Depletion (AD), among others, were used sparsely (<30 % of the 35 LCA-based studies
 573 reviewed). Despite their lower adoption, the presence of this large number of indicators suggests
 574 that MIs sustainability assessment draw on a wide array of metrics and environmental factors.
 575 Biodiversity-oriented indicators, such as stock depletion (2.9%) or Net Primary Production

576 Demand (NPPU) (5.9%), are employed even less frequently, pointing to either a lack of
 577 appropriate metrics or insufficient emphasis to this crucial aspect in MIs research. Additionally,
 578 other marine-related impacts, such as seabed impact (Woods and Verones, 2019), discards
 579 (Vázquez-Rowe et al., 2012) and plastic emissions (Hajjar et al., 2023), remain underrepresented.
 580 This gap highlights the need for broader adoption and further developments in marine-focused
 581 methods in scientific literature.

582 **4.2.1 How do commonly analyzed environmental impacts influence the Marine Ingredients** 583 **(MIs) industry assessment?**

584 Aquaculture feed consistently emerges as the main environmental hotspot in many of the studies
 585 reviewed (see comparison in Table 2), largely due to the production, transportation and milling of
 586 feed ingredients (Bosma et al., 2011; Konstantinidis et al., 2021). The differences between
 587 aquaculture species can be explained by the feed conversion ratio (FCR), the type of system used,
 588 and the composition of the feed (i.e., marine or plant-based ingredients). The origin of these
 589 ingredients is a major driver of overall supply chain impacts (Basto-Silva et al., 2019; Wilfart et
 590 al., 2023), as well as a significant contributor to GW indicator (Wind et al., 2022). For LU impact
 591 category, the major burdens in aquaculture ingredients production usually stem from agricultural
 592 requirements for plant-based inputs (Wilfart et al., 2023; Konstantinidis, et al., 2021). Marine-
 593 derived components also contribute significantly to GW, largely due to the harvesting process
 594 (Samuel-Fitwi et al., 2013), but their exact impact can vary based on the aquaculture system and
 595 species farmed (Bordignon et al., 2023). For example, farming carnivorous species requires
 596 higher quantities of wild-caught fish, which can contribute significantly to environmental burdens
 597 (Naylor et al., 2000).

598 **Table 2.** Average environmental impact value of aquaculture by main species: values per kg of fish and per
 599 kg of feed. The range of values for each species, both maximum and minimum, are shown in parentheses.

Fish Specie	Average value per kg of fish				
	GW (kg CO ₂ eq)	Eu (kg PO ₄ ³⁻ eq)	Ac (kg SO ₂ eq)	LU (m ² year)	WU (m ³)
Rainbow trout ^{1,2,3,4}	1,76 (1,18-3,16)	0,04 (0,007-0,064)	0,01 (0,006-0,029)	3,24 (1,63-4,85)	12,78 (10,3-15,2)
Tilapia ^{1,5}	1,65 (0,80-2,89)	0,08 (0,054-0,105)	0,02 (0,010-0,029)	14,26	1,06
Crustaceans ⁶	9,09	0,006	0,005	4,17	8,40
Salmon ^{2,7}	10,35 (5,04-13,2)	0,11 (0,031-0,149)	0,12 (0,033-0,158)	-	-
Carp ⁵	1,81(1,75-1,88)	0,13 (0,10-0,15)	0,02 (0,014-0,016)	-	-
Pangasius ²	8,93	0,070	0,050	-	-
Fish Specie	Average value per kg of feed				
	GW (kg CO ₂ eq)	Eu (kg PO ₄ ³⁻ eq)	Ac (kg SO ₂ eq)	LU(m ² year)	WU (m ³)
Rainbow trout ⁸	1,76	0,051	0,021	1,88	11,86
Crustaceans ⁶	1,16	-0,002	0,002	2,69	0,67
Salmon ^{7,9}	5,68 (3,96-8,55)	0,074 (0,003-0,099)	0,044 (0,015-0,060)	-	-
Pangasius ²	2,37 (2,02-2,55)	0,003 (0,0021-0,0036)	0,023 (0,0184-0,0258)	-	-

1) Avadi et al., 2015; 2) Bosma et al., 2011; 3) Wilfart et al., 2023; 4) Wind et al., 2022; 5) Mungkung et al., 2013; 6) Bohnes & Laurent, 2021; 7) Parker, 2018; 8) Wilfart et al., 2023; 9) Couture et al., 2019.

GW: Global Warming; Eu: Eutrophication; Ac: Acidification; LU: Land use; WU: Water use.

600 Including SCP formulations (e.g., yeast or bacteria) in feed can substantially reduce multiple
601 environmental impact indicators as compared to soy concentrate-based formulations. However,
602 SCP can increase GW due to the use of methane as a substrate, and the overall benefit is offset by
603 other components of the feed (Couture et al., 2019). Similarly, the impact of diets high in animal
604 BPs (from poultry or mammals) can be significant; although, the magnitude of the impact depends
605 largely on the allocation rule chosen. This is a relevant methodological consideration when
606 comparing results between studies (Parker, 2018).

607 Another study shows that choosing a multi-objective formulation that cuts FMFO by half and
608 eliminates soy and gluten can reduce the environmental impact of feed and farm production
609 without compromising growth. Consequently, lower GW were observed for trout than for more
610 intensive carnivorous species (Wilfart et al., 2023). Likewise, diets with a certain fraction of FM
611 performed better than a 100% plant-based option in the categories analyzed by how oilseed crops
612 would be formulated (Wind et al., 2022). Similarly, increasing the proportion of FMFO from
613 trimmings offered more advantages than substituting by insect meals (Bohnes & Laurent, 2021).
614 Meanwhile, feed processing itself significant affects GW, EP, RU (Mungkung et al., 2013;
615 Konstantinidis et al., 2021), and OD impacts (Hilmarsdóttir et al., 2022).

616 Within FMFO production plants, the rendering stage contributes notably to GW and Ac (Campos
617 et al., 2020). Steam generation for drying is identified as one of the most environmentally
618 intensive contributors (Fréon et al., 2017) and plays a crucial role in terms of fossil energy
619 consumption, depending on the fuel used (Smáráson et al., 2017; Hilmarsdóttir et al., 2022). For
620 example, switching from fuel oil to natural gas can significantly reduce environmental impacts,
621 independently of FM quality or yield (Fréon et al., 2017; Deville et al., 2025). This is relevant,
622 because environmental impacts have also been found to differ depending on FM quality (Laso et
623 al., 2016). It is also worth noting that lower grade FM has been associated with higher
624 environmental impact compared to premium FM (Fréon et al., 2017), often due to carbon and air
625 pollution intensive energy matrix and lower raw material yield (Avadí et al., 2015). Additional
626 challenges surface with FM originating from mixed fisheries, which have been identified as a
627 major contributor to GW, through primary production needs (McKuin et al., 2023; Couture et al.,
628 2019). Indeed, global fishing fleet fuel use and derived GHG emissions have been increasing
629 significantly in recent decades (Parker et al., 2018), which could be attributed to needs to travel
630 further or into deeper waters (Free et al., 2019). Fuel use intensity (FUI), expressed as liters or
631 kilograms of diesel per unit of catch, serves as a common index for quantifying this impact
632 (Newton et al., 2023). FUI is specially elevated in high demand fishery operations such as
633 trawling, compared to less fuel-intensive methods such as purse seining (Newton et al., 2023,
634 Vázquez-Rowe et al., 2010). Consequently, Cashion et al. (2017) suggest that the environmental
635 impact from white fish BPs was higher due to the FUI of demersal fisheries and the low yields

636 from rendering, particularly for FM. Conversely, low-trophic level pelagic species and their BPs,
637 such as Peruvian anchoveta, generally exhibit lower levels of impact in conventional LCA
638 categories (Newton et al., 2023), partly due to the energy-efficient purse seine fishing techniques
639 and high anchoveta yield rates in MIs production (Deville et al., 2025).

640 Beyond these direct environmental effects, there also concerns about limited availability of data
641 for assessing social LCA and cost-benefit analyses in the Peruvian MIs sector (Avadí et al., 2014;
642 Cashion et al., 2017). Avadí et al. (2014), integrated material flow models, sustainability
643 indicators, and multi-criteria approach for Peruvian MIs industry to explore three scenarios:
644 maintaining current anchoveta exploitation levels, increasing landings for DHC, or reducing total
645 landings to support other fish stocks. Their findings concluded that increasing anchoveta landings
646 for DHC results in stronger overall sustainability improvements than either maintaining or
647 reducing exploitation levels. In its assessment of the social aspects, it points out that fishing and
648 related industries create many jobs, but there is overcapacity in the industrial fleet and FM
649 factories in Peru, which reduces efficiency and creates labor problems in the sector. Based on this
650 insight it is interesting to debate whether MIs remains the most convenient option in terms of
651 environmental sustainability, under current conventional metrics and business/market models.
652 Future aquaculture research may thus benefit from pinpointing specific areas for process-level
653 improvement (Hilmarsdóttir et al., 2022), expanding and updating LCA databases for MIs and
654 alternative ingredients (Silva et al., 2018) and refining knowledge of nutritional requirements in
655 feed formulations (Samuel-Fitwi et al., 2013). Multitarget feed development holds particular
656 promise for reducing environmental burdens, as highlighted by Wilfart et al. (2023), who
657 emphasize the potential of more comprehensive formulations to drive sustainability gains.

658 **4.3 Current needs in the Marine Ingredients (MIs) for new metrics and novel impact** 659 **categories in pollution footprint and emergent contaminants**

660 Dietary exposure plays a significant role in transmitting persistent and environmental chemicals
661 to fish (Xiao et al., 2015). Although direct uptake from water is predominantly observed,
662 absorption through feed is less studied and can notably influence the bioaccumulation of certain
663 chemicals (Wang & Wang, 2005), primarily via passive diffusion through the fish body and
664 gastrointestinal tract (Xiao et al., 2015). However, our current understanding of future exposure
665 to these pollutants remains limited, a gap that becomes evident in the lack of extensive data on
666 contamination, additives, and antibiotics in the MIs supply chain (Ghamkhar et al., 2020).
667 Consequently, aquatic animals' meat can also be contaminated with these chemicals, posing
668 potential health risks when consumed (Jennings et al., 2016).

669 Persistent organic pollutants (POPs), including dioxins and polychlorinated biphenyls (PCBs),
670 have been found to accumulate in fish (Strobel et al., 2016), and can be linked to their feeding

671 habits and position in the food chain (Corsolini et al., 2005). POPs have been detected in
672 numerous fish species across different regions worldwide, underscoring their widespread
673 distribution and bioaccumulation (Jeong et al., 2020). In the context of BPs, contaminants may
674 persist through valorization processes and waste treatment often resulting in FM, evidencing the
675 importance of understanding POPs impact in aquatic ecosystems and their potential human health
676 implications, particularly in relation to seafood consumption. (Lopes et al., 2015)

677 The existence of microplastics (MPs) also represents another significant environmental concern,
678 with growing research documenting their widespread presence in aquatic ecosystems (e.g.,
679 Caruso, 2019; Thiele et al., 2021). MPs can reduce natural prey intake among fish and
680 invertebrates, affecting in growth, reproduction, and survival rates (Foley et al., 2018), while also
681 acting as vectors for contaminants and pathogens, potentially altering their toxicity,
682 bioavailability, and fate in aquatic environments (Huang et al., 2021).

683 The relationship between MPs, environmental pollutants, and microbial genetics in aquaculture
684 is complex. Dong et al. (2021) explain that the combined presence of MPs and antibiotic
685 resistance mechanisms can amplify contamination risks, exposing both human health and
686 ecological stability. This concern grows with the widespread use of FM in aquaculture, where
687 bacterial communities exhibiting antibiotic resistance are increasingly observed (Han et al.,
688 2017). However, currently available data is insufficient for detailed investigations.

689 Substantial information gaps persist regarding the end fate of MPs (Pauna & Askham, 2022),
690 highlighting the need for more studies on their long-term impact on aquatic organisms and
691 potential implications for human health (Elizalde-Velázquez & Gómez-Oliván, 2021).
692 Recognizing these data limitations, novel impact categories designed to capture marine plastic
693 pollution, covering nano/micro and macroplastics, are emerging in LCA methods (Woods et al.,
694 2021). A first set of LCA-oriented studies focused on the endpoint effect factors for entanglement
695 of biota due to macroplastics (Woods et al., 2019) and the fate of MPs (Saling et al., 2020).
696 However, these approaches were considered preliminary and not yet sufficient for widespread
697 application in general LCA studies, because it was necessary to understand how plastics degrade
698 and fragment in the ocean (Boulay et al., 2021). For LCA purposes, inventory data should be
699 regionalized and include attributes such as size, material, and density. Moreover, the different
700 routes of exposure to plastic waste (e.g., ingestion, entanglement and suffocation) must be better
701 understood, and how they behave during marine environment interactions (Woods et al., 2021).

702 Recent efforts have refined these methodologies. Pauna & Askham (2022), for example, proposed
703 a methodological approach to validate MPs emission by linking emission estimates to site-specific
704 environmental observations. Lavoie et al. (2022) developed effect factors to quantify physical
705 effect of MPs and nanoplastics damage to aquatic species, positioning these hazards relative to

706 moderate toxic chemicals already included in USEtox. Subsequently, Corella-Puertas et al.
707 (2023), introduced updated characterization factors for aquatic emissions impacts of MPs and
708 nanoplastics (NPs), differentiating polymers by shape and size, developing target factors for 11
709 different polymers, three profiles (sphere/microsphere, cylinder/microfiber, microplastic film
710 fragments) and five sizes (1, 10, 100, 1000, 5000 μm), to yield a more detailed and representative
711 environmental assessment. The inclusion of physical effects on biota as an impact category in the
712 GLAM (LCI, 2025) and Impact World+ v2.1 (Impact World+, 2025) methods in late 2024
713 suggests that its use in LCA literature may become mainstream in upcoming years.

714 **4.4 Non-LCA conventional indicators to assess marine ingredients sustainability**

715 LCA serves as a valuable framework for quantifying environmental impacts in both fisheries and
716 aquaculture. In aquaculture, LCA-based research often centers on evaluating new feed
717 formulations; yet commonly used indicators may not capture the full complexity of sustainability
718 and diversity of impacts associated with these activities, particularly regarding MIs (Table 3).

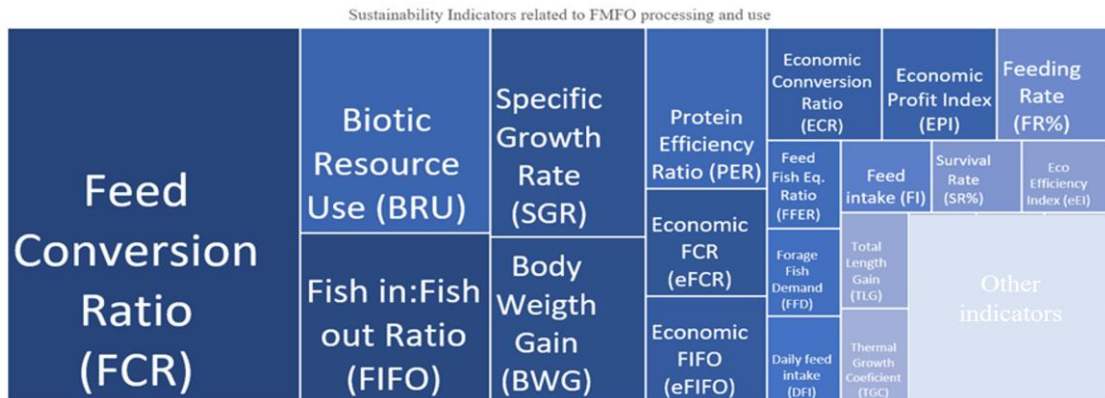
719 In fisheries, historical gaps in marine-specific impact categories led researchers to rely on
720 indicators that emphasize direct interactions with marine ecosystems, such as Biotic Resource
721 Use (BRU), Forage Fish Demand (FFD), and Biocapacity (BC), without fully employed life cycle
722 thinking logically in their modelling. Some of these have been highlighted as useful for evaluating
723 commercial fisheries and sustainable management of marine resources and their impact on marine
724 ecosystems (Buonocore et al., 2021; Pikitch et al., 2014; Niccolucci et al., 2012). However, for
725 FM production, which acts as a bridge between fisheries and aquaculture, metrics like BRU and
726 Fish-In: Fish-Out (FIFO), integrate economic considerations into ecological and environmental
727 assessment (Newton et al., 2023). This is especially relevant to MIs, as it highlights production
728 efficiency over time through innovation in the aquafeed industry (Tacon & Metian, 2008),
729 although current LCA methodologies do not account for the specific health of fisheries and their
730 sustainable exploitation levels (Newton et al., 2023).

731 Our systematic review reveals some non-LCA conventional indicators that dominate
732 sustainability evaluations of MIs in the aquaculture. Of these, the FCR, used in 35% of the studies,
733 emerges as the most common reference, reflecting the efficiency with which fish convert feed
734 into biomass (see Figure 6). Thereafter, BRU (13%) considers the origin and composition of feed,
735 frequently involving FMFO derived from wild fish stocks. Finally, FIFO

736 **Table 3.** Description of the conventional non-LCA indicators for environmental sustainability assessment of marine ingredients, mainly fishmeal and fish oil, studies analyzed
 737 in this review. Each indicator has a description of the acronym, the type of assessment criteria and the scope of the indicator.

Sustainability Indicators	Acronym	Assessment Criteria			Industrial Scope			References
		Environment.	Ecological	Economic	Fish Performance	Fisheries	MIs	
Biotic Resource Use	BRU	X	X			X	X	<i>Newton et al., 2023; Cashion et al., 2016; Couture et al., 2019; Avadí et al., 2015; McKuin et al., 2023; Jóhannesson et al., 2019</i>
Fish in: Fish out Ratio	FIFO		X		X	X	X	<i>Stejskal et al., 2023; Kok et al., 2020; Newton et al., 2023; Stejskal et al., 2020; Tran et al., 2022</i>
Forage Fish Demand	FFD		X			X		<i>Cottrell et al., 2020</i>
Eco Efficiency Index	eEI	X	X				X	<i>García-Santiago et al., 2021</i>
Gross Energy Content	GEC				X			<i>Avadí et al., 2014</i>
Energy Return on Investment	EROI	X		X			X	<i>Avadí et al., 2014</i>
Biocapacity	BC		X			X		<i>Jóhannesson et al., 2019</i>
Impacts Biotic Natural Resources	IBNR	X	X			X		<i>Avadí et al., 2014</i>
Trophic level on Landings	Tlland		X			X		<i>Avadí et al., 2014</i>
Feed Conversion Ratio	FCR				X		X	<i>Wilfart et al., 2023; Hender et al., 2021; Avadí et al., 2015; Stejskal et al., 2023; Bohnes & Laurent, 2021; Shaw et al., 2022; Sandström et al., 2022; Cottrell et al., 2020; Parker, 2018; Van Phi et al., 2020; Mungkung et al., 2013; Smáráson et al., 2017; Bosma et al., 2011; Wind et al., 2022; Konstantinidis et al., 2021; Stejskal et al., 2020; Tran et al., 2022</i>
Specific Growth Rate	SGR				X		X	<i>Wilfart et al., 2023; Hender et al., 2021; Stejskal et al., 2023; Shaw et al., 2022; Stejskal et al., 2020</i>
Body Weight Gain	BWG				X		X	<i>Wilfart et al., 2023; Hender et al., 2021; Stejskal et al., 2023; Shaw et al., 2022</i>
Economic FCR	eFCR			X				<i>Nhu et al., 2016; Kok et al., 2020</i>
Economic FIFO	eFIFO			X			X	<i>Kok et al., 2020; Tran et al., 2022</i>
Economic Conversion Ratio	eCR			X			X	<i>Stejskal et al., 2023; Stejskal et al., 2020</i>
Economic Profit Index	EPI			X			X	<i>Stejskal et al., 2023; Stejskal et al., 2020</i>
Protein Efficiency Ratio	PER				X		X	<i>Stejskal et al., 2023; Stejskal et al., 2020</i>
Daily feed intake	DFI				X		X	<i>Wilfart et al., 2023</i>
Feed intake	FI				X		X	<i>Stejskal et al., 2023</i>
Feeding Rate	FR%				X		X	<i>Stejskal et al., 2023; Shaw et al., 2022</i>
Survival Rate	SR%				X		X	<i>Hender et al., 2021</i>
Total Length Gain	TLG				X		X	<i>Shaw et al., 2022</i>
Feed Fish Eq. Ratio	FFER		X	X		X		<i>Nhu et al., 2016</i>
Thermal Growth Coefficient	TGC				X		X	<i>Shaw et al., 2022</i>

739 (10%) is commonly used to measure the net fish biomass input required to produce the output
 740 fish biomass, underscoring the ongoing reliance on marine resources in aquaculture systems.



741
 742 **Figure 6.** Tree-map used to represent sustainability non-LCA conventional indicators related to the
 743 processing and use of fishmeal and fish oil. The dimension of each rectangle corresponds to the
 744 importance or weight of each indicator in the context of use in studies related to the sustainability of
 745 marine ingredients.

746 **4.4.1 Feed Conversion Ratio – FCR**

747 FCR (ratio of total feed input to biomass gain) is considered a critical indicator in aquaculture,
 748 (Avadí et al., 2015). Lower FCR values indicate greater efficiency (Stejskal et al., 2023), reducing
 749 the demand for wild-caught fish used in FMFO production, alleviating pressure on wild fisheries
 750 (Rodde et al., 2020; Inayat & Salim, 2005). However, as shown in Table 4, salmonids species
 751 demonstrate the highest dependence on FMFO alongside the best conversion efficiency. This
 752 efficiency correlates with key environmental incomes: direct relationship has been documented
 753 between FCR and both GW and Ac, suggesting that better feed formulations leading to lower
 754 FCR can help mitigate such effects (Konstantinidis et al., 2021). Bosma et al. (2011) covered this
 755 connection by showing how high FCR in Pangasius farming was the primary reason in
 756 contribution of most impact categories compared to more efficient fish farming systems.
 757 Additionally, FCR improvements can significantly reduce Eu, LU, and WU, further underscoring
 758 its importance in the sustainability of aquaculture systems (Bohnes & Laurent, 2021; Mungkung
 759 et al., 2013).

760 **Table 4.** Description of main fed fish and crustacean species in aquaculture, alongside an estimate of
 761 compound feed usage and their correspondent feed conversion ratio (FCR) (Adapted from Tacón, 2019).

Farmed fish and crustaceans	Production based on fish feeds (%)	Average FCR
Fed carps	57	1.7
Tilapia	92	1.7
Shrimp	86	1.6
Marine fish	82	1.7
Salmon	100	1.3
Freshwater crustaceans	57	1.8
Trout	100	1.3

762 Recent advances in nutritional science have shown that high-quality protein in aquafeeds
763 improves FCR and reduces the environmental burdens of fish farming (Glencross et al., 2023;
764 Luthada-Raswiswi et al., 2021). However, aquafeed that offers better FCR does not guarantee, on
765 its own, better overall environmental performance per kg of fish. This is because greater
766 refinement and transportation of inputs is needed (Avadí et al., 2015). Even so, there is also a
767 clear link between body weight gain and FCR, with rapid growing species displaying lower ratios
768 (Rodde et al., 2020). Moreover, the incorporation of alternative feed ingredients has emerged as
769 a strategy to reduce the reliance on traditional fish-based feeds diets (Bohnes & Laurent, 2021;
770 Cottrell et al., 2020).

771 In parallel, technological innovations, such as precision feeding (where feed quantities are fine-
772 tuned to meet specific growth stage demands) offer a promising path to improve FCR
773 (Konstantinidis et al., 2021). Similarly, genetic selection methods also show significant potential
774 for boosting FCR efficiency in aquacultural species (Natale et al., 2013). In this context, applying
775 ex-ante (Cucurachi et al., 2018) and prospective LCA (Thonemann et al., 2020) studies to these
776 emerging strategies would continue to improve aquaculture LCA studies, capturing the full
777 impact of technological progress in feed management.

778 From an economic perspective, FCR strongly influences profitability, as suboptimal FCR values
779 reduce returns per unit of produced biomass (Cottrell et al., 2020). On the downside, however,
780 conventional FCR measurement is frequently vulnerable by time-consuming processes and
781 limited accuracy (Li et al., 2014). Moreover, FCR fails to account for differences in feed
782 composition, edible portions, nutritional quality of the final product, and timing (Fry et al., 2018).
783 In practice, feed intake-weight gain ratios can fluctuate over time (Rodde et al., 2020), and shift
784 with temperature changes and altered feeding rates (Bethkeet al., 2013). Some researchers
785 therefore propose alternative metrics such as "nutrient retention" which provide a more nuanced
786 view of feed efficiency (Fry et al., 2018).

787 The Economic Feed Conversion Ratio (eFCR) is known as an evolution of the FCR metric,
788 incorporating economic considerations to quantify how much feed is required to support 1 ton of
789 fish net biomass growth over the farming period (Nhu et al., 2017). Despite its potential utility,
790 particularly given by feed price volatility and differences in species growth rates), except the case
791 of Nhu et al., (2017), no studies in our review directly integrate economic values into FCR in
792 LCA calculation. However, future studies could benefit from applying eFCR or similar metrics to
793 offer a perspective of profitability within aquaculture systems.

794 **4.4.2 Biotic Resource Use – BRU**

795 Despite recent efforts oriented towards capturing the depletion of target biotic resources (Hélias
796 et al., 2023), most published LCA studies still omit the status of fisheries and the extent of their
797 sustainable exploitation (Newton et al., 2023). Newly proposed impact categories, which include
798 biomass extraction and its associated effects on marine biodiversity and population health
799 (Stanford-Clark et al., 2024), helps to fill some existing gaps. Moreover, though its inclusion in
800 the Impact World+ v2.1 method (in parallel with emerging approaches for plastic emission
801 impacts), suggest it will see broader adoption in the near future.

802 However, the studies reviewed here have encountered difficulties in quantifying the
803 environmental repercussions of biomass removal from wild stocks. To address this limitation,
804 many have employed the BRU indicator, which tracks the primary productivity needed to sustain
805 fish production based on both FCR and the primary productivity consumed via feed (Avadí et al.,
806 2015). In fisheries, BRU typically focuses on catch volume, whereas aquaculture tends to measure
807 resources in terms of MIs in feed (Natale et al., 2013), underscoring different strategies involved
808 in marine resource management. Nonetheless, as Cashion et al. (2016) note, the complexity of
809 data collection and interpretation often present challenges in seafood LCAs, potentially leading
810 to an underestimation of impacts in more traditional methods.

811 Moreover, the choice of LCA methodologies and system boundaries can greatly influence how
812 BRU is evaluated. For example, environmental impacts in aquaculture, such as Eu and Ac, are
813 highly dependent on feed sourcing and nutrient recycling, both of which directly affect the BRU
814 metric (Pelletier & Tyedmers, 2010). Consequently, current challenges with employing BRU in
815 aquaculture LCA arise from operational factors, framework methodological variations, data
816 availability issues, and the need to incorporate biodiversity considerations into a holistic
817 environmental performance assessment.

818 **4.4.3 Fish in:Fish out – FIFO**

819 FIFO is a metric that offers a way to measure aquaculture's environmental sustainability by
820 assessing how much wild-caught fish is required to produce an equivalent volume of farmed fish
821 (Kok et al., 2020). A high FIFO ratio suggests greater reliance on marine resources, which may
822 lead to the risk of unsustainable practices, including overfishing or inadequate management of
823 wild fish stocks (Stejskal et al., 2020).

824 Reduction of this ratio typically depends on improving FCR, reducing the inclusion of MIs in
825 feed, and replacing whole fish FM with FM from trimmings (Naylor et al., 2021). However, FIFO
826 are related to considerable variability due to differences in yields, inclusion rates and FCR that
827 depends on species, location and the management practices, and they may also average
828 herbivorous and carnivorous fish species, disguising the elevated MIs requirements of certain
829 species (Majluf et al., 2024).

830 Recent studies, (Kok et al., 2020; Stejskal et al., 2023), highlight the potential unsustainability
831 due from high FIFO ratios when aquaculture relies heavily on wild fish for feed. At the same time,
832 it can be problematic with low FIFO values, which can lead to incorrect assumptions about self-
833 sufficiency, given that FIFO does not account for non-fishery-based feed inputs (Majluf et al.,
834 2024). Advancements in feed composition, such as inclusion of insect meals, can reduce FIFO
835 and encourage more sustainable aquaculture practices (Stejskal et al., 2023), but this often
836 increases pressure on other ecosystems (e.g., terrestrial ecosystems). Moreover, many calculations
837 methods overlook different uses of MIs, or the relative scarcity of FO compared to FM. For
838 species with high oil demands, this neglect can intensify fishing pressure, emphasizing the need
839 for more accurate metrics that include all MIs uses (Kok et al., 2020).

840 Additional factors such open water aquaculture pollution, feed scarcity and space availability are
841 also relevant, where the FIFO ratio of different species varies significantly, due to different
842 aquaculture practices (Regnier & Schubert, 2014). Biofouling and the management of aquaculture
843 BPs further complicate sustainability assessment of MIs, but these are rarely directly included in
844 FIFO calculations (Fitridge et al., 2012; Stevens et al., 2018).

845 Because existing FIFO methods do not fully capture the wide environmental impacts of
846 aquaculture, researchers have criticized limited alignment with life cycling thinking approaches
847 (Kok et al., 2020). An alternative way to capture other viewpoints is the economic FIFO (eFIFO),
848 which integrates economic considerations by quantifying how much feed is financially required
849 to support 1 kg of fish growth (Kok et al., 2020). For example, Tran et al., (2022), illustrate how
850 combining FIFO and eFIFO metrics in conjunction with LCA can improve the evaluations of
851 environmental impacts linked to replacing FM with insect meal in fish diets.

852 Using economic allocation within eFIFO, a concept commonly used in LCA of MIs, provides a
853 market-based view of ingredients value (especially relevant in understanding more limited co-
854 products like FO) (Kok et al., 2020). However, reliance on price faces limitations faces inherent
855 challenges, such as price volatility and weak correlation between price and physical flows
856 (Ardente & Cellura, 2012). Additionally, price difference in FO, as demonstrated in the studies
857 by Kok et al. (2020) and Shaw et al. (2022), can particularly bias eFIFO for species with highly
858 dependence on FO.

859 Overall, the evolution from traditional to economic FIFO metrics illustrates the dynamic nature
860 of sustainability assessments in aquaculture. Refining these methodologies to better incorporate
861 environmental, economic and social dimensions, would offer a more complete picture of true
862 aquaculture sustainability.

863 **5. Conclusions and future needs for MIs sustainability metrics**

864 The aquaculture industry has experienced exponential growth in recent decades, positioning itself
865 as a viable solution for meeting the global demand for protein and seafood products. However,
866 this rapid expansion has also raised considerable concerns about the sustainability of the MIs and
867 the challenges associated with their use. Developing sustainable fishing practices and identifying
868 alternative sources of protein for aquaculture feed are therefore vital to achieve a balance between
869 marine preservation, economic growth and human well-being. One of the primary challenges lies
870 in the adequate assessment of the environmental sustainability of these ingredients using current
871 LCA metrics and related non-LCA indicators, each of which has several limitations that require
872 comprehensive review.

873 Based on our critical review, we find that current sustainability metrics do not adequately capture
874 the intricate and varied nature of aquaculture on a global scale. In fact, the aquaculture sector
875 encompasses a broad number of species with diverse nutritional requirements, cultivated across
876 multiple regions with significant ecological and socioeconomic differences. Standardizing
877 methodologies without sufficient consideration to regional differences often leads to partial or
878 biased assessments. For instance, a uniform approach fails to adequately reflect the disparities in
879 environmental impact between salmon production in Norway and tilapia farming in tropical
880 regions. On the one hand, conventional LCA methods and the associated indicators tend to
881 emphasize certain impact categories, such as GW (present in all LCA studies analyzed), as the
882 expense of other critical impacts, including biodiversity loss, overfishing and marine habitat
883 degradation. Non-LCA metrics, like the FCR, can further compound these issues, such as
884 prioritizing short-term food efficiency over long-term ecological sustainability, particularly given
885 the inherent complexity and sensitivity of marine ecosystems to human activities.

886 Another pressing concern is the lack of metrics to adequately address the presence of non-
887 regulated contaminants in MIs, including additives, antibiotics and MPs. The absence of robust
888 widely accepted LCA impact categories hinder effective evaluation and decision-making derived
889 from LCA interpretation. Encouragingly, new LCA metrics and assessment methodologies are
890 beginning to emerge, some of which have already been released and briefly discussed in this
891 review, that could offer the potential to address the current limitations. These include methods
892 that quantify direct biodiversity impacts and expand environmental impact categories to include
893 novel entities, like seabed damage and physical effects on biota due to plastic emissions. At the
894 same time, accurately quantifying the damage on marine biodiversity remains a highly complex
895 process, that encompasses genetic factors, species and ecosystem diversity. Additionally, growing
896 interest in CLCA approaches could facilitate a more holistic understanding of the consequences
897 of varying ingredient proportions in aquaculture feeds formulations, although it may increase
898 complexity and uncertainty.

899 In any case, it is evident that the current metrics are insufficient for fully assessing the global
900 sustainability of fish processing BPs, particularly in contrast to their conventional use in FMFO.
901 Alternatives such as DHC, production of high-value-added bioproducts, or application in
902 agriculture as biofertilizers, could potentially offer higher environmental and socioeconomic
903 benefits. However, the limited availability of indicators that incorporate these possibilities limit
904 the capacity to investigate, communicate and promote more sustainable utilization of these
905 resources over the long term, thereby limiting their potential contribution to a sustainable solution
906 for the world's supply. In parallel, exploring alternative protein sources, like plant-based proteins,
907 insects, and single-cell proteins (SCP), offers a promising opportunity to alleviate the pressure on
908 wild fish populations in feed manufacturing. Nevertheless, these alternatives must be subjected
909 to a rigorous environmental assessment of using robust methodologies to analyze their
910 sustainability and real productive advantages and drawbacks at realistic scales, where such scales
911 exist.

912 Looking ahead, future research into MIs sustainability, must critically reconsider the current
913 methodologies and metrics. A more comprehensive, holistic and regionally tailored approach, one
914 that accounts not only for direct environmental impacts but also for socioeconomic factors and
915 sustainable alternatives for use of marine resource, will be mandatory. Progress in developing
916 more precise and wide-ranging assessment tools will be essential for the advancement of a
917 responsible and sustainable aquaculture industry that recognizes and respects the needs of both
918 marine ecosystems and the communities that depend on them.

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922 **Credit authorship contribution statement**

923 **David Baptista de Sousa:** conceptualization, resources, methodology, formal analysis,
924 investigation, data curation, visualization; writing first draft - **Ian Vázquez-Rowe:**
925 conceptualization, formal analysis, writing - review & editing, supervision, project
926 administration; **Ramzy Kahhat:** conceptualization, formal analysis, writing - review & editing,
927 supervision; project administration.

928

929 **Declaration of Competing Interest**

930 The authors declare no conflict of interest.

931

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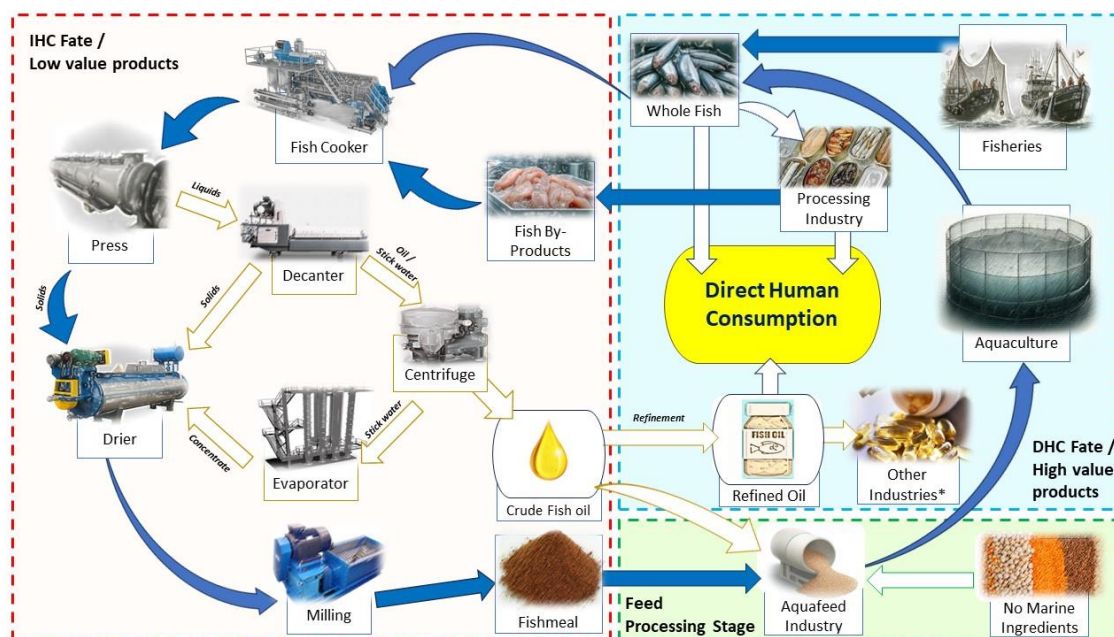


Figure 1. Graphical representation of the main industrial processes from marine ingredients (MIs) The red dotted line delineates the steps involved in indirect human consumption (IHC) for fishmeal (FM) and fish oil (FO) processing. First, the raw material is cooked to denature the proteins and release the oil. Subsequently, the liquid is separated through pressing and used to produce FO. The solid residue is dried and crushed to produce a final fine powder. Both FM and FO are the result of the same production procedure. The blue dotted line illustrates the source of resource utilization for direct human consumption (DHC) as high-value products (*Other industries of refined oil use: pharmaceutical, cosmetic, petfood; etc.); The green dotted line encompasses the aquafeed processing steps derived from diverse ingredient origins. White arrows indicate the intended destination for DHC. Blue arrows indicate a potential destination for IHC. Yellow arrows indicate the fish oil cycle. Green arrows indicate the vegetal or non-marine material origin.

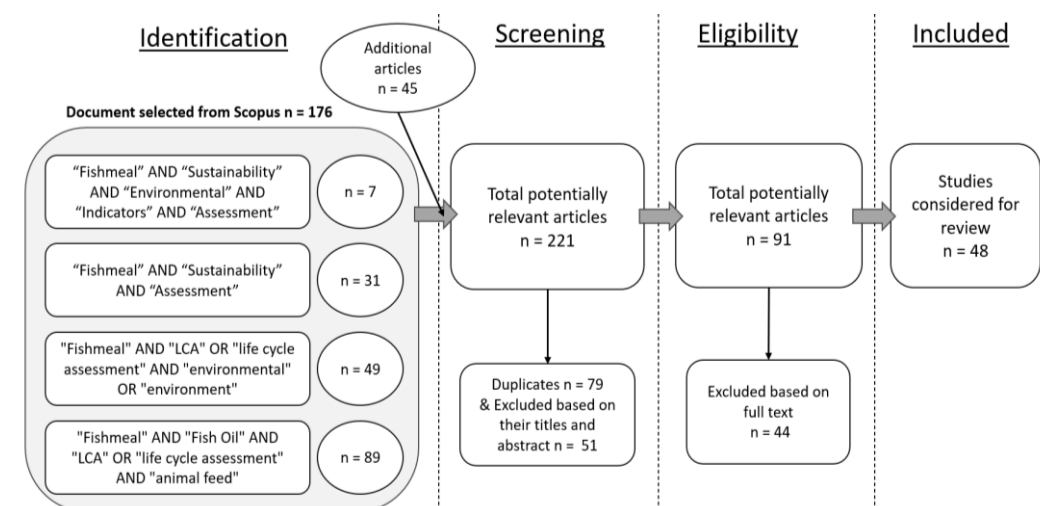


Figure 2. Flow chart of the selection process of studies for the systematic review.

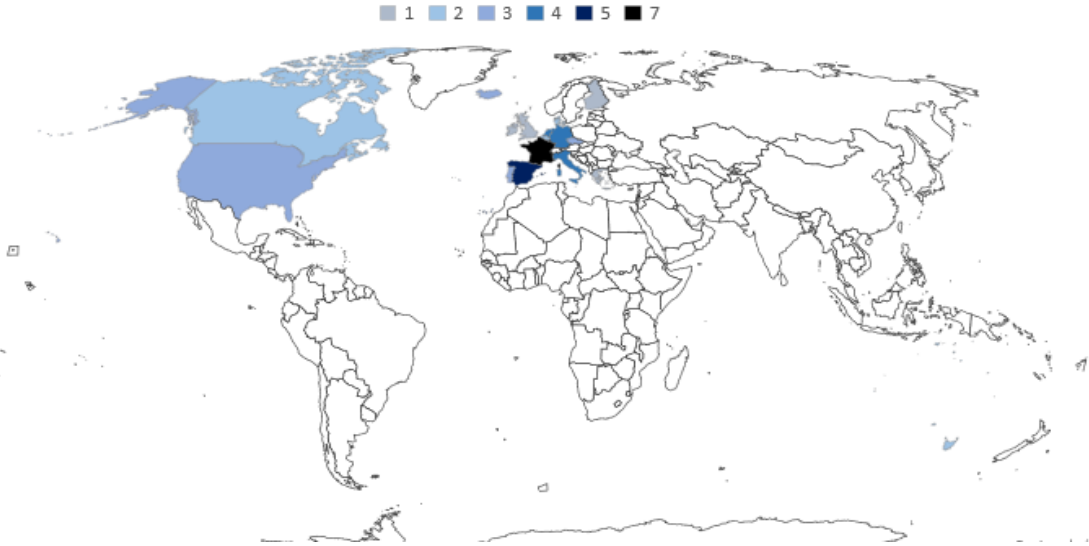


Figure 3. Geographic distribution of marine ingredients sustainability related studies included in the review. Increasing color intensity indicates a higher count in the number of studies included in the review performed. To establish geographical classification, the first author's affiliation has been identified as a key criterion for consideration.

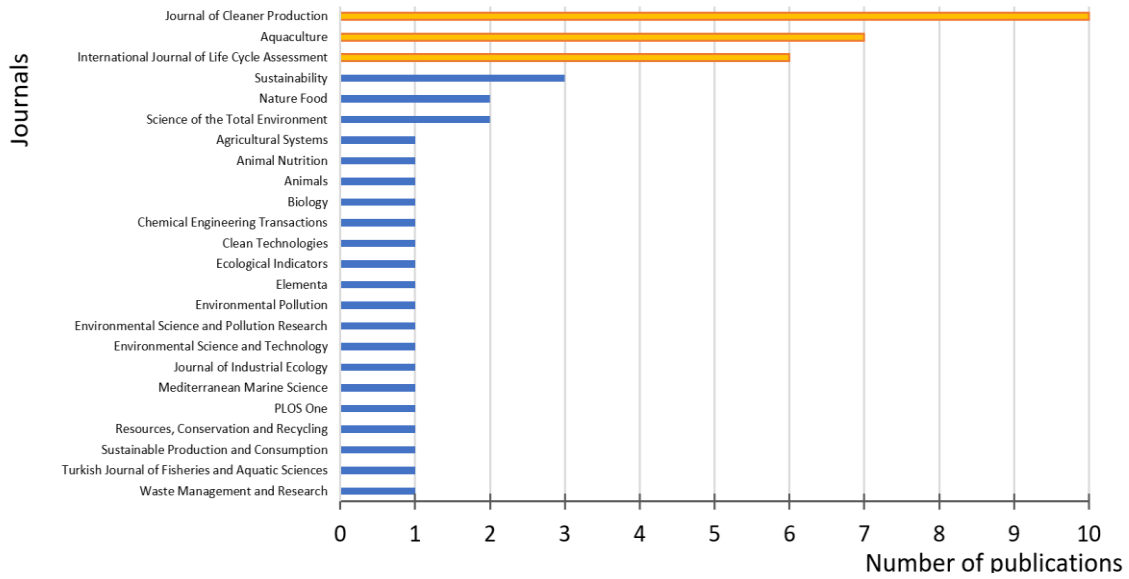


Figure 4. Distribution of the 48 publications examined in the current marine ingredients' sustainability assessment review in scientific research journals. All publications were published within the 2013-2023 timeframe. Results are presented from highest to lowest number of publications in each journal, with the orange bars representing the journals that had the highest number of articles on the topic evaluated.

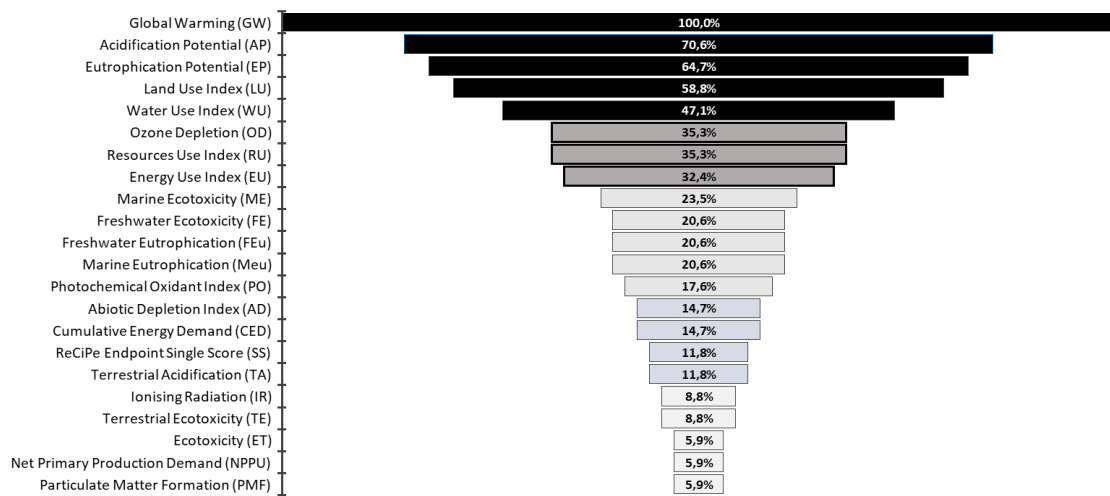


Figure 5. Main environmental impact indicators used in Marine Ingredients (MIs), mainly fishmeal and fish oil, sustainability assessment. Each horizontal bar represents a different indicator, and the length of the bar indicates the percentage of the rating that indicator represents in the number of times used in the publication of the review.

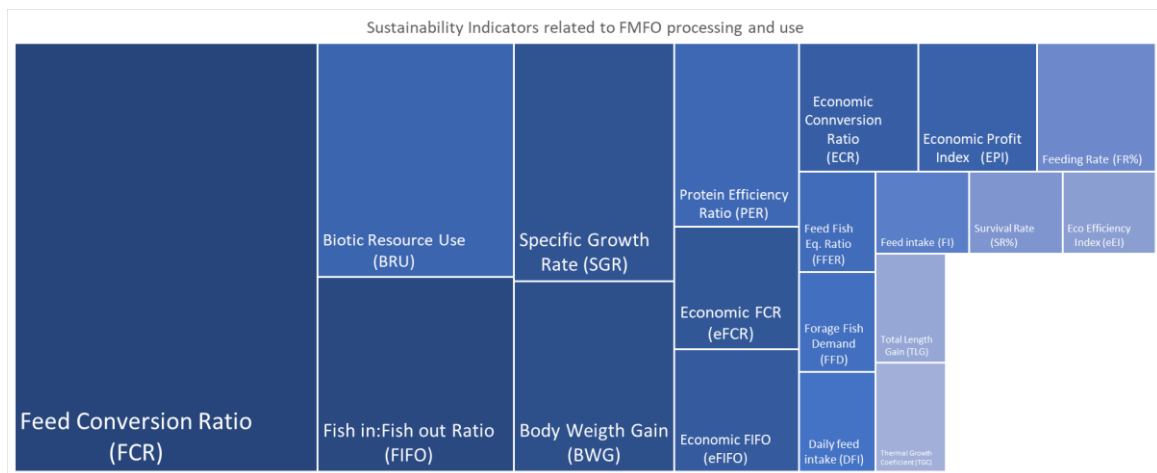


Figure 6. Tree-map used to represent sustainability non-LCA conventional indicators related to the processing and use of fishmeal and fish oil. The dimension of each rectangle corresponds to the importance or weight of each indicator in the context of use in studies related to the sustainability of marine ingredients.

Table 1. Summary of main characteristics of the reviewed Life Cycle Assessment (LCA) studies include the perspective (i.e., attributional or consequential), Life Cycle Impact Assessment (LCIA) method, allocations, functional unit, and topic.

Authors	Perspective	LCIA Method	Allocation	FU	Topic
MIs PROCESSING/ BPs PROCESSING AND VALORIZATION TO MIs					
Avadí et al., 2014	ALCA	ReCiPe/ CMLbl 2000/CED/USEtox	N/A	1 t of landed anchoveta	Assessment of DHC vs IHC of Peruvian anchoveta
Avadí et al., 2015	ALCA	CML 2 / ReCIPE	Mass-GEC	1 t live weight, fresh farmed fish	Comparison of commercial versus artisanal feeds in Peruvian freshwater aquaculture
Cortés et al., 2021	ALCA	Recipe 2016	Economic	1 t of raw tuna at processing plant gate	Multiproduct strategic in tuna can industry study
Fréon et al., 2017	ALCA	ReCiPe	Mass/Economic	1 t output-based & process-based FM	FM Processing LCA
García-Santiago et al., 2021	ALCA	ReCiPe Midpoint (H) method	Mass	100 kg of whole cartilaginous fish	Marine biorefinery for valorization versus conventional MIs
Hilmarsdóttir et al., 2022	ALCA	ReCiPe 2016	Energy	1 t fishmeal and fish oil	Study of MIs production plant in Iceland; Raw material acquisition and processing
Laso et al., 201 ^a	ALCA	iCheme, 2002	N/A	1 can of final product	LCA study to identify BAT in the anchovy canning sector
Laso et al., 2016b	ALCA	iCheme, 2002	Economic	1 t of anchovy wastes	LCA study on canning factory anchovy process with MIs production
Laso et al., 2018	ALCA	IPCC 2013 / CML/ ReCIPE	N/A	1 kg of anchovy	Anchovy-based products for IHC (FM) and for direct human consumption
Newton et al., 2023	ALCA	CML Baseline	Mass/Economic	1 t MI produced	Evaluation of MI process efficiency
Silva et al., 2018	ALCA	CML-IA baseline V3.04	Mass	1 t of ingredient used	FM substitution in feed: sardine and tuna fish and Peruvian anchovy
Togarcheti et al., 2021	ALCA	CML	Mass	1 kg EPA+DHA	Evaluation of FO extraction methodologies
MIs ASSESSMENT IN FEEDS/DIETS					
Basto-Silva et al., 2019	ALCA	Recipe	Mass	1 kg of experimental diet	Experimental diets replacement of MIs
Beyers et al., 2023	CLCA	Environmental Footprint 3.0	Economic	1 t protein in livestock feed	Diet comparison with conventional MIs use
Bohnes & Laurent, 2021	ALCA.	IPCC; CML-IA; IMPACT World+; USEtox; AWR	Mass/Economic	1 t of edible seafood	Assess the conventional MIs ingredient substitution with trimmings or insects
Bordignon et al., 2023	A/CLCA	CML-IA method	N/A	1 kg of diet production	Study of diets with substitution of FO alternatives
Bosma et al., 2011	ALCA	ReCiPe-2008/ CML2	Mass	1 ton of fresh fish	Environmental impacts in the production of striped catfish in intensive farming systems
Campos et al., 2020	ALCA	CML	Economic	1 t of ingredient to fish feed producer	Compare different feedstuff for aquaculture vs MIs, replacing FO and FM.
Couture et al., 2019	ALCA	ReCiPe	Economic	1 kg of feed	Evaluation of use of SCP for Feeds Analysis
Ferronato et al., 2023	ALCA	IMPACT 2002+	N/A	1 t of OFMSW	FM substitution for alternative ingredients
Goyal et al., 2021	ALCA	ReCiPe 2016	Mass	1 kg LH pellets	Study of diet substitution of conventional FM with insects
Konstantinidis et al., 2021	ALCA	ReCiPe 2016	Mass/Energy	1 t of harvested fish	Comparing diets: identify environmental hotspots linked to fish feeds granulations
Maiolo et al., 2020	ALCA	CML-IA method	Mas/Economic	1 t of protein content	Assessment of 4 partial FM substitutes in diets formulation of new aquafeeds
McKuin et al., 2023	ALCA	ReCiPe 2016;	Economic	1 kg crude protein	Study of diets with alternative ingredients for FM substitution
Mungkung et al., 2013	ALCA	CML2 Baseline 2000 method	Mass/Economic/Energy	1 t of fresh fish delivered to the market	Diets in environmental impacts associated with two-net cage aquaculture systems
Nhu et al., 2016	ALCA	RECIPE; Natural Environment (CEENE)	Mass/Economic/Exergy	1 t live weight of Pangasius	Comparison between Pangasius produced on ASC farm & non-ASC intensive farms
Parker, 2018	ALCA.	ReCiPe method / CML-IA Baseline	Mass/Economic/Energy	1 kg of head-on gutted (HOG) salmon	Use of animal by-product inputs in aquaculture feeds
Penaranda et al., 2023	ALCA	Environmental footprint (EF) / CED	Economic	1 kg microalgae & 1 kg meal as feed.	Algae meal was compared with fishmeal for feed uses
Roffeis et al., 2020	ALCA	ReCiPe	Economic	1 kg IBM	Comparison of Insect based diet versus conventional FM in fish
Samuel-Fitwi et al., 2013	A/CLCA	CML 2000	Mass	1 t of rainbow trout feed	Trout diet assessment by different formulation
Smáráson et al., 2017	ALCA	CML 2 Baseline 2000 / CED	Mass	1 kg of live-weight Arctic char	Experimental diets replacement (conventional meal vs vegetal meal vs insect meal)
Van Phi et al., 2020	ALCA	IMPACT 2002+	Economic	1 t of IM equivalent to 1.03 t of FM	Compare Insect Meal versus conventional Fishmeal
Van Zanten et al., 2015	ALCA	IPCC	Economic	1 t larvae meal on dry matter basis	Evaluation of ingredient substitution in livestock feed
Wilfart et al., 2023	ALCA	ILCD / CML	N/A	1 kg of body-weight gain	Assessment of Feed formulas; Feed digestibility; Growth performance in fish
Wind et al., 2022	ALCA	CML-IA baseline	Mass/Energy	1 kg fish live weight	Comparison of plant-based vs fish-based feed diet

DHC: direct human consumption; IHC: indirect human consumption; GEC: Gross Energy Content; BAT: best available techniques; FM: fishmeal; FO: fish oil; MIs: fishmeal/fish oil; SCP: single cell protein; OFMSW: organic fraction of municipal solid waste; LH: combination of *Lemma minor* and *Hermetia illucens* meal; IBM: insect base meal; IM: insect meal; LCA: life cycle assessment; ALCA: Attributional LCA; CLCA: Consequential LCA.

Table 2. Average environmental impact value of aquaculture by main species: values per kg of fish and per kg of feed. The range of values for each species, both maximum and minimum, are shown in parentheses.

Fish Specie	Average value per kg of fish				
	GW (kg CO ₂ eq)	Eu (kg PO ₄ ³⁻ eq)	Ac (kg SO ₂ eq)	LU (m ² year)	WU (m ³)
Rainbow trout ^{1,2,3,4}	1,76 (1,18-3,16)	0,04 (0,007-0,064)	0,01 (0,006-0,029)	3,24 (1,63-4,85)	12,78 (10,3-15,2)
Tilapia ^{1,5}	1,65 (0,80-2,89)	0,08 (0,054-0,105)	0,02 (0,010-0,029)	14,26	1,06
Crustaceans ⁶	9,09	0,006	0,005	4,17	8,40
Salmon ^{2,7}	10,35 (5,04-13,2)	0,11 (0,031-0,149)	0,12 (0,033-0,158)	-	-
Carp ⁵	1,81(1,75-1,88)	0,13 (0,10-0,15)	0,02 (0,014-0,016)	-	-
Pangasius ²	8,93	0,070	0,050	-	-
Fish Specie	Average value per kg of feed				
	GW (kg CO ₂ eq)	Eu (kg PO ₄ ³⁻ eq)	Ac (kg SO ₂ eq)	LU(m ² year)	WU (m ³)
Rainbow trout ⁸	1,76	0,051	0,021	1,88	11,86
Crustaceans ⁶	1,16	-0,002	0,002	2,69	0,67
Salmon ^{7,9}	5,68 (3,96-8,55)	0,074 (0,003-0,099)	0,044 (0,015-0,060)	-	-
Pangasius ²	2,37 (2,02-2,55)	0,003 (0,0021-0,0036)	0,023 (0,0184-0,0258)	-	-

1) Avadi et al., 2015; 2) Bosma et al., 2011; 3) Wilfart et al., 2023; 4) Wind et al., 2022; 5) Mungkung et al., 2013; 6) Bohnes & Laurent, 2021;

7) Parker, 2018; 8) Wilfart et al., 2023; 9) Couture et al., 2019.

GW: Global Warming; Eu: Eutrophication; Ac: Acidification; LU: Land use; WU: Water use.

Table 3. Description of the conventional non-LCA indicators for environmental sustainability assessment of marine ingredients, mainly fishmeal and fish oil, studies analyzed in this review. Each indicator has a description of the acronym, the type of assessment criteria and the scope of the indicator.

Sustainability Indicators	Acronym	Assessment Criteria				Industrial Scope			References
		Environment.	Ecological	Economic	Fish Performance	Fisheries	MI	Aquaculture	
Biotic Resource Use	BRU	X	X			X	X		<i>Newton et al., 2023; Cashion et al., 2016; Couture et al., 2019; Avadí et al., 2015; McKuin et al., 2023; Jóhannesson et al., 2019</i>
Fish in: Fish out Ratio	FIFO		X		X	X	X	X	<i>Stejskal et al., 2023; Kok et al., 2020; Newton et al., 2023; Stejskal et al., 2020; Tran et al., 2022</i>
Forage Fish Demand	FFD		X			X	X		<i>Cottrell et al., 2020</i>
Eco Efficiency Index	eEI	X	X				X	X	<i>García-Santiago et al., 2021</i>
Gross Energy Content	GEC				X			X	<i>Avadí et al., 2014</i>
Energy Return on Investment	EROI	X		X			X	X	<i>Avadí et al., 2014</i>
Biocapacity	BC		X			X			<i>Jóhannesson et al., 2019</i>
Impacts Biotic Natural Resources	IBNR	X	X			X			<i>Avadí et al., 2014</i>
Trophic level on Landings	Tiland		X			X			<i>Avadí et al., 2014</i>
Feed Conversion Ratio	FCR				X		X	X	<i>Wilfart et al., 2023; Hender et al., 2021; Avadí et al., 2015; Stejskal et al., 2023; Bohnes & Laurent, 2021; Shaw et al., 2022; Sandström et al., 2022; Cottrell et al., 2020; Parker, 2018; Van Phi et al., 2020; Mungkung et al., 2013; Smáráson et al., 2017; Bosma et al., 2011; Wind et al., 2022; Konstantinidis et al., 2021; Stejskal et al., 2020; Tran et al., 2022</i>
Specific Growth Rate	SGR				X			X	<i>Wilfart et al., 2023; Hender et al., 2021; Stejskal et al., 2023; Shaw et al., 2022; Stejskal et al., 2020</i>
Body Weight Gain	BWG				X			X	<i>Wilfart et al., 2023; Hender et al., 2021; Stejskal et al., 2023; Shaw et al., 2022</i>
Economic FCR	eFCR			X				X	<i>Nhu et al., 2016; Kok et al., 2020</i>
Economic FIFO	eFIFO			X			X	X	<i>Kok et al., 2020; Tran et al., 2022</i>
Economic Conversion Ratio	eCR			X			X	X	<i>Stejskal et al., 2023; Stejskal et al., 2020</i>
Economic Profit Index	EPI			X			X	X	<i>Stejskal et al., 2023; Stejskal et al., 2020</i>
Protein Efficiency Ratio	PER				X			X	<i>Stejskal et al., 2023; Stejskal et al., 2020</i>
Daily feed intake	DFI				X			X	<i>Wilfart et al., 2023</i>
Feed intake	FI				X			X	<i>Stejskal et al., 2023</i>
Feeding Rate	FR%				X			X	<i>Stejskal et al., 2023; Shaw et al., 2022</i>
Survival Rate	SR%				X			X	<i>Hender et al., 2021</i>
Total Length Gain	TLG				X			X	<i>Shaw et al., 2022</i>
Feed Fish Eq. Ratio	FFER		X	X		X	X		<i>Nhu et al., 2016</i>
Thermal Growth Coefficient	TGC				X			X	<i>Shaw et al., 2022</i>

Table 4. Description of main fed fish and crustacean species in aquaculture, alongside an estimate of compound feed usage and their correspondent feed conversion ratio (FCR) (Adapted from Tacon, 2019).

Farmed fish and crustaceans	Production based on fish feeds (%)	Average FCR
Fed carps	57	1.7
Tilapia	92	1.7
Shrimp	86	1.6
Marine fish	82	1.7
Salmon	100	1.3
Freshwater crustaceans	57	1.8
Trout	100	1.3