Aquaculture 600 (2025) 742239

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Identifying current trends in the environmental impacts linked to fishmeal and fish oil production in Peru

Alejandro Deville [a,*], Ian Vázquez-Rowe [a], Angel Avadí [b,c], Fernando Miranda [d], Ramzy Kahhat [a]

[a] Peruvian Life Cycle Assessment & Industrial Ecology Network (PELCAN), Department of Engineering, Pontificia Universidad Católica del Perú, Av. Universitaria 1801, San Miguel 15074, Lima, Peru

[b] CIRAD, UPR Recyclage et risque, Yamoussoukro, Côte d'Ivoire

[c] Recyclage et Risque, Univ Montpellier, CIRAD, Montpellier, France

[d] Austral Group S.A.A., Austevoll Seafood Company, Av. Victor Andrés Belaúnde N° 147, San Isidro 15073, Lima, Peru

ARTICLE INFO

Keywords:
Climate change
Engraulis ringens
Fisheries
Fish oil
Fishmeal
Industrial ecology
Life cycle assessment

ABSTRACT

The anchoveta (*Engraulis ringens*) fishery in Peru, which is almost entirely devoted to the production of fishmeal and fish oil, is one of the largest fisheries in the world. It is volatile in terms of fishing stock availability, and the fishmeal industry has been subject to technological changes to upgrade its efficiency and reduce costs to maintain its competitiveness. The objective of this study is to apply the Life Cycle Assessment methodology to the production and exportation of fishmeal and fish oil products related to a relevant producer in Peru, representing 10 % of national production. A set of 169 vessels targeting *E. ringens* were inventoried, 88 % of which are owned by third parties, and four factories belonging to the company were assessed for the years 2019 and 2021. Ecoinvent was the selected database to support the life cycle inventory, and ReCiPe 2016 and IPCC 2021 were the methods applied to compute the environmental impacts. The results show that fuel combustion in fishmeal and fish oil production was the dominating activity in most of the impact categories analyzed. In terms of greenhouse gas emissions, it was found that, on average, approximately 320 kg CO_2eq and 4430 kg CO_2eq are emitted due to the production of 1 t of fishmeal and 1 t of fish oil, respectively, when an energy allocation is followed. The fishery accounted for ca. 45 % of greenhouse gas emissions and dominated most of the impact categories, showing greater influence of the fishing stage than in previous studies. The reasons behind are linked to the combined influence of improvements in the energy matrix of the plants, by prioritizing natural gas over diesel and residual fuel oils, and a slightly higher fuel use intensity of the fishing fleet. *E. ringens* quality was found to be an important parameter, as low protein or fat yields translate into substantially higher impacts. Finally, although Peruvian fishmeal and fish oil remain as one of the lowest environmental footprint products among animal feed, future work is needed to understand the effects that climate change and El Niño-Southern Oscillation events have on this industry.

1. Introduction

Fishmeal and fish oil (FMFO) production are critical raw materials produced mainly for their use as aquafeed in the aquaculture sector (Glencross et al., 2024). In fact, animal feed, which is typically composed of an important dose of fishmeal and, to a lesser extent, fish oil (Avadí et al., 2015), has been identified as one of the main contributors to environmental impact in the supply chain (MacLeod et al., 2020). Although FMFO are usually seen as a homogeneous set of products, the species from which FMFO is produced can affect the final nutritional composition of farmed animals (Fiorella et al., 2021). Beyond aquaculture, fishmeal is a typical ingredient for feeds used in the livestock industry (Kok et al., 2020) and as pet food (Shepherd and Jackson, 2013). Similarly, fish oil is used in multiple markets for direct or indirect human consumption, although the former is limited to fish oils with high content of long-chain omega-3 polyunsaturated fatty acids, such as eicosapentaenoic acid and docosahexaenoic acid (Swanson et al., 2012).

Despite its dwindling weight in global FMFO trade, Peru is still the main producer worldwide, representing roughly one-third of the total value of fishmeal exports in 2022 (FAO, 2024). The anchoveta (*Engraulis ringens*) fishery in the Peruvian Exclusive Economic Zone (EEZ) has

* Corresponding author.
E-mail address: alejandro.deville@pucp.edu.pe (A. Deville).

https://doi.org/10.1016/j.aquaculture.2025.742239
Received 6 August 2024; Received in revised form 29 October 2024; Accepted 28 January 2025
Available online 30 January 2025

shown to be one of the most productive and largest fisheries worldwide (Chávez et al., 2008; Moron et al., 2019). It is also the largest fishery worldwide that is almost entirely devoted to reduction (Shepherd and Jackson, 2013), with a vast network of reduction plants throughout the Peruvian coast (Wintersteen, 2021). However, in a similar way to most pelagic fish caught for reduction, *E. ringens* is a suitable species for direct human consumption (DHC) (Cashion et al., 2017), although efforts by the Peruvian government to introduce *E. ringens* as a source of protein in Peruvian diets have essentially failed (Sánchez-Durand and Gallo-Seminario, 2009; Paredes, 2023).

El Niño-Southern Oscillation (ENSO) has traditionally been an important threat to the FMFO industry in Peru (Bertrand et al., 2020). Cold currents present during *La Niña* tend to fill the holds of purse seiners targeting *E. ringens* throughout the Peruvian coast (Bertrand et al., 2020). In contrast, moderate to strong *El Niño* events bring warm currents to the Peruvian coast, displacing *E. ringens* stocks towards the coast (Bertrand et al., 2008, 2020), where industrial fishing vessels are banned from extracting in the first 5 nautical miles (Jara et al., 2020).

Given the importance of these marine ingredients in the aquafeed international market, FMFO production has become of interest from an environmental impact perspective (Kok et al., 2020), in an effort to make commercial formulations for aquaculture and livestock not only more efficient regarding nutritional aspects, but also in terms of an array of diverse environmental aspects, such as climate change (Jannathulla et al., 2019), human- and/or eco-toxicity (Jonell and Henriksson, 2015) and more recently, impacts on marine ecosystem quality due to biotic resource depletion during fishing (Hélias et al., 2023; Stanford-Clark et al., 2024) and plastic pollution (Corella-Puertas et al., 2023; Mahamud et al., 2022; Wang et al., 2022). In this context, Life Cycle Assessment (LCA) is an internationally standardized methodology that aims at identifying the environmental impacts along supply chains with the ultimate goal of determining the environmental hotspots of the system under analysis, which can be useful in terms of cleaner production, policy or corporate decision-making, eco-design, among others. Hence, LCA is the process of assessing the effects that a product or service has on the environment over its entire lifetime (i.e., from material extraction to end-of-life treatment) with the aim to increase resource-use efficiency and identifying environmental trade-offs (European Environment Agency, 2017). The use of LCA has become common in the seafood sector (Ziegler et al., 2016), especially for industrial fisheries (Gephart et al., 2021) and processing (Coelho et al., 2023), as well as aquaculture (Bohnes and Laurent, 2019), mainly in the Global North (Ruiz-Salmón et al., 2021).

LCA literature on marine ingredients in general, and FMFO in specific, is scarce (Glencross et al., 2024). Most of the available literature has focused on Peruvian *E. ringens*, both regarding fisheries (Fréon et al., 2014; Avadí et al., 2014) and reduction processes (Fréon et al., 2017), although other studies have been published for The Gambia (Avadí and Acosta-Alba, 2021) or Vietnam (Horsnell, 2018). In parallel, a study by Kok et al. (2020) coupled LCA with Fish In: Fish Out (FIFO) ratios, determining that allocation of environmental flows to either fishmeal or fish oil can have an important influence on the results, altering the final message delivered to decision-makers. The study states that fed aquaculture produces up to four times the amount of fish compared to what it consumes (FIFO $\approx$1/4), but when using an economic allocation approach, the species with a higher oil requirement led to a significantly increased FIFO, due to increasing prices of fish oil (Kok et al., 2020). Moreover, the ecoinvent® database, a comprehensive Life Cycle Inventory (LCI) database on the environmental flows of over 20,000 products and services (Ecoinvent, 2024a, 2024b) incorporated FMFO datasets (Avadí et al., 2020) based on those published by Fréon et al. (2017). Although these datasets can be accessed without allocation, ecoinvent applies an economic allocation perspective for the separate FMFO datasets. Scarce datapoints for FMFO environmental profiles in the scientific literature add uncertainty when it comes to understand their global environmental performance, but also that of food products, mainly from the aquaculture and livestock sectors, that have a high dependence on these products in feed formulation.

In this context, the main objective of this study was to estimate the environmental impacts using LCA of the production of FMFO products in 4 reduction plants along the Peruvian coast belonging to Austral Group S.A.A., one of the main producers of FMFO in Peru and worldwide. The results obtained intend to provide an update of previous LCA studies conducted in Peru for the same purpose about a decade ago (Avadí et al., 2014; Fréon et al., 2014, 2017), analyzing the technological changes in the fishing fleet and reduction plants and their effect on environmental impacts, as well as delivering results for new impact categories that have been developed in recent years. Moreover, the impact of methodological decisions (e.g., allocation perspective, completeness or data availability and quality) were also analyzed in depth. We consider that these results are of importance at a global scale given the relevance of Peruvian FMFO in international trade, especially in the two main markets worldwide: China and the European Union. We expect fishery and LCA-related scientists, FMFO producers, stock assessment specialists, policymakers and stakeholders in the aquaculture sector to be the main target audience of this study.

2. Materials and methods

2.1. Goal and scope

The main goal of this study was to measure the environmental impacts linked to the production of FMFO following the LCA methodology (ISO, 2006). For this, 4 FMFO production plants were analyzed along the Peruvian coast, three located in north-central Peru, in which landings from the Northern stock arrive (i.e., Coishco, Chancay and Pisco) and one located in southern Peru, in which *E. ringens* from the Southern stock is landed, i.e., Ilo (Fig. 1).

We used data from the stock assessments developed in 2019 and 2021, in which Austral Group S.A.A. contributed to 320,187 t (1.6 %) and 517,192 t (2.5 %) of worldwide catch intended for FMFO production, respectively. In addition, the company's fishmeal and fish oil production in 2019 was 76,082 t and 11,051, t, respectively, representing 1.5 % and 1.0 % of worldwide production. In year 2021 the values were somewhat higher, with fishmeal at 122,165 t (2.5 %) and fish oil at 15,869 t (1.3 %). Year 2020 was discarded as it was a highly anomalous year due to the temporal closure of the industry as a result of the COVID-19 pandemic. More recent years were not available at the time of the study.

The function established for the production system was the delivery of a certain amount of fishmeal for indirect human consumption (IHC) or fish oil for either DHC or IHC. Hence, the mathematical relation established (i.e., the functional unit – FU) to present the environmental impacts was 1 t of fishmeal or 1 t of fish oil placed at a receiving port in the country importing the load.

The system boundary of the production system includes the productive phase that comprises the fishing phase (extractive stage) and the conversion to final product (transformation stage to FMFO). Additionally, the study also considers the subsequent transport to the port of destination (Fig. 2) in the importing country.

It should be noted that the fishing phase is carried out by a considerable number of vessels. On the one hand, some, that belong to the company, are permanent within fishing operations and recurrently land at the *chatas* (i.e., coastal floating infrastructure through which the *E. ringens* is landed and sucked into the FMFO plant) during the fishing season. On the other hand, other vessels belong to an independent fleet of opportunistic vessels, which we refer to in this paper as "third-party vessels", landing at the *chata* whenever FMFO plants need additional landings for their production objectives.

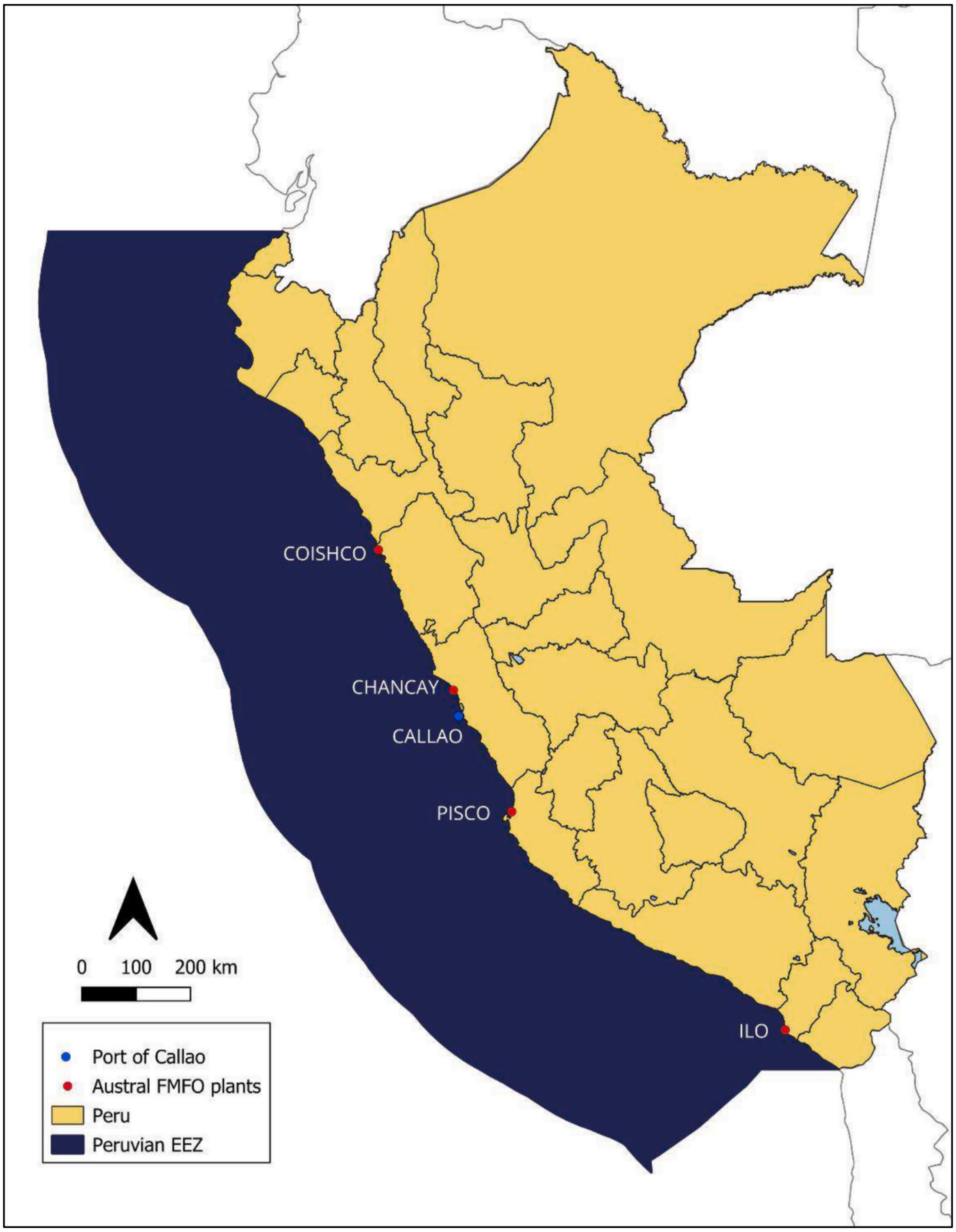

Fig. 1. Location of the fishmeal and fish oil (FMFO) plants along the Peruvian coast analyzed in this study.

2.2. Multifunctionality and allocation

FMFO production constitutes a multifunctional process in which two co-products are generated (i.e., fishmeal and fish oil). Moreover, their production process is indivisible through most of the processing phase, as there are multiple recirculation stages in which the two production lines interact intermittently with the aim of maximizing production. Given these characteristics, and following the ISO guidelines (ISO, 2006), allocation was conducted to establish a modeling framework that allows for a distinguishable mathematical computation of the two processes. However, allocation practices in LCA are controversial, as the partitioning is linked to indivisible processes (Pelletier and Tyedmers, 2011) that are allocated based on a particular attribute, that is usually either biophysical (e.g., energy content, round weight, etc.) or economic (Ruiz-Salmón et al., 2021). While there is abundant bibliography that discusses allocation in LCA studies (Weidema and Schmidt, 2010; Pelletier et al., 2015), analyzing the pros and cons of different approaches, in this study, we have chosen to prioritize the use of an energy content-based allocation, based on the fact that both products are: i) transformed mainly for the feed industry, in which energy content is critical to feed different aquaculture or livestock species; and, ii) important contributors to the economic revenue of FMFO plants, especially considering the increasing price of fish oil as a commodity in the international market (see Figure SM1 in the Supplementary Material – SM). Nonetheless, in the present analysis, three different types of allocation have been considered, two biophysical (i.e., energy and mass weight) and one economic (i.e., monetary value) with the aim of reducing uncertainties and so that the carbon footprint obtained can be compared with various case studies in the scientific literature.

The prioritized allocation perspective was determined according to the energy content of the products, using the energy contents reported by Fréon et al. (2017). The second allocation method, by mass, was

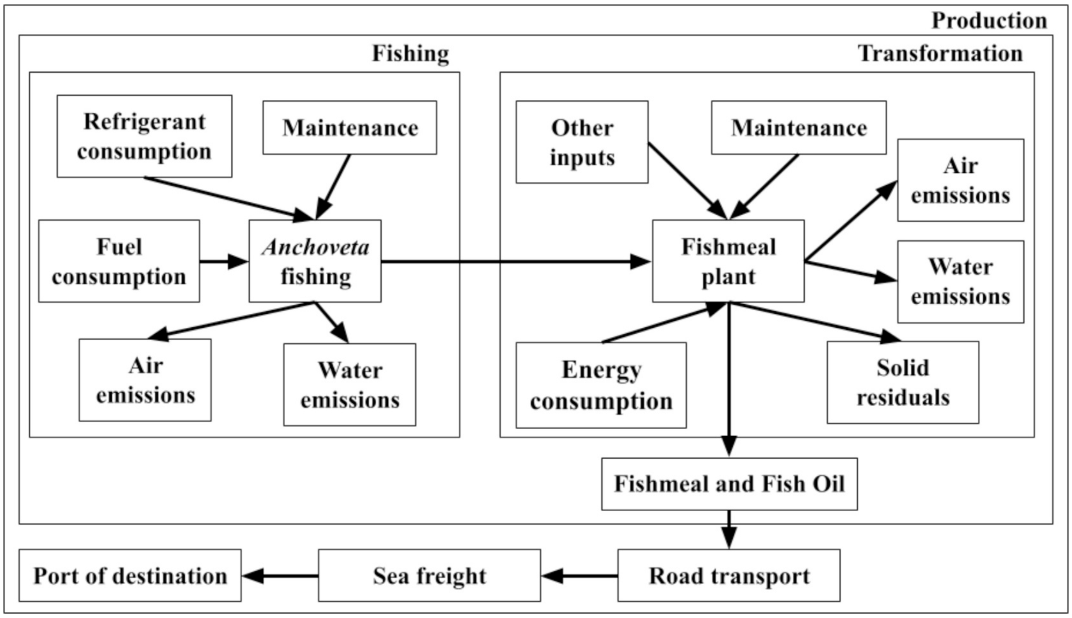

Fig. 2. Schematic representation of the system boundary of the production system. The fishing stage considers anchoveta (*Engraulis ringens*) fishing activities and landing at the fishmeal plant. The transformation stage includes the landing of *E. ringens* and its transformation to fishmeal and fish oil (FMFO). The production stage considers both the fishing and transformation phases. Finally, transportation to the destination port is considered.

obtained from the weight distribution of the finished products reported by the FMFO company. Finally, the analysis with economic allocation considered the sale prices of FMFO for both study years, published by the Peruvian Central Bank (Banco Central de Reserva del Perú, 2023a; 2023b) (Figure SM1 in the SM). Nonetheless, it is important to consider that there were no site-specific data on the energy content of FMFO, so a reference value was taken from Fréon et al. (2017), which considers an allocation of 34 % for fishmeal and 66 % for fish oil. The energy content of FMFO depends primarily on the quality of the raw material, which can vary considerably between regions and seasons. Additionally, the energy content values found in the literature do not differentiate between DHC and IHC oil. Therefore, the energy content was calculated according to the weight proportion of the total oil produced. Likewise, when applying economic allocation, the prices reported by the Peruvian Central Bank do not distinguish between DHC and IHC oil (Banco Central de Reserva del Perú, 2023b).

2.3. Data collection

The data used to develop the LCI were based on primary data collected and transferred by the analyzed FMFO company. Firstly, a 20-h course was held with technical staff from Austral Group S.A.A., with the aim of explaining the principles of life cycle thinking and methods. Thereafter, a technical visit to the plants of Coischco and Chancay, in northern Peru, was performed by the LCA team. Once the visit was completed, and once the technical staff that would support data gathering was defined, a questionnaire for the different stages of the production system was built and delivered to the company, with the aim of gathering high quality primary data.

The foreground system was based on primary data collected by the company through questionnaires regarding vessel and fishing information, as well as the production inputs and outputs. It also includes transport to the port of destination, for which detailed information regarding road transport and marine transport for both products was collected by the company. In contrast, the background data of this study used secondary inventory data from the ecoinvent 3.8 database. Data collection was carried out by the Research and Development Division at Austral Group S.A.A., which provided detailed information for each plant and year. For the fishing phase, data included fuel consumption and landed catch, as well as a quantification of other inputs, such as lubricant oil, cooling agents, and fishing gear. Capital goods, such as fishing equipment and construction and maintenance materials, were also reported together with the physical characteristics of the vessels (i.e., length, beam, hold capacity).

For the transformation stage, a detailed description of the machinery, materials used (e.g., iron sulfate and acetic acid), energy (i.e., fuels and electricity) and water consumption, or the use of packaging materials, were reported on an annual basis, among other inputs and outputs. Moreover, the quality and performance of the *E. ringens* was included. Finally, for the transport phase, data regarding the road transport to the port of Callao, as well as maritime transport to the port of destination were provided.

Although the data provided were comprehensive, the composition of a small amount of ingredients, mainly those with commercial names, such as “Optisperse”, “Permax”, and certain enzymes, was not provided and could not be included in the modeling. Likewise, other substances such as antioxidants (ethoxyquin, BHA and BHT) were modeled using a generic ecoinvent process (i.e., “Chemical, organic {GLO}| market for | APOS, U"). Although products that were not included could have important impacts depending on their production processes, we hypothesize that these changes would not generate a statistically significant difference. In fact, FMFO transformation in 2019 used over 1700 t of production inputs (excluding energy inputs and landed *E. ringens*), whereas only 19 t (ca. 1.1 % by weight) of inputs were not included due to the limitations abovementioned. Similarly, in 2021, only 21 t out of a total of 2700 t of inputs (i.e., 0.78 %) were not introduced in the model.

2.4. Life cycle modeling

The LCI was modeled using the SimaPro Software v9.5.0.2 (PRé, 2024). The foreground system was modeled mainly with the primary and secondary data described in subsection 2.3, whereas the background system was modeled entirely with the ecoinvent 3.8 database. An allocation at point of substitution (APOS) system model was selected for the background unit processes, assuming a shared responsibility for waste flows between producers and subsequent users along the supply chain (Ecoinvent, 2024a, 2024b).

2.5. Life cycle impact assessment

The assessment methods used to compute the potential environmental impacts were ReCiPe 2016 v1.1 with a hierarchical perspective (Huijbregts et al., 2017) for a wide array of impact categories, and IPCC 2021 with a timeframe of 100 years for the case of global warming (Pörtner et al., 2022). While most results are presented as midpoint indicators, endpoint results using *ReCiPe 2016 Endpoint (H) v1.1/World (2010)* H/A are also briefly discussed and fully reported in Table SM25 of the SM.

Uncertainty was computed for greenhouse gas (GHG) emissions calculated with the IPCC 2021 method using Monte Carlo (MC) simulation. For this, pseudo-random values (10,000 iterations) were generated for each datapoint (i.e., elementary flow) based on their probability distribution. Uncertainty factors of all the inputs and activities were calculated with the Pedigree matrix, in which data reliability, completeness, temporal, geographical and technological correlations are used as indicators (scored from 1 to 5) and transformed to calculate the geometric standard deviation (Ciroth et al., 2016). This distribution was in most cases (ca. 75 %) lognormal for the background data, whereas for the foreground data it was fully modeled under lognormal distribution.

3. Results

This section presents the LCI and Life Cycle Impact Assessment (LCIA) results for all the stages of the production and transport of FMFO products for the years 2019 and 2021. Firstly, the LCI is presented, including information on the fishing and transformation phases, as well as the data on FMFO terrestrial and marine freighting. Secondly, the environmental performance of the fishing phase is presented. Thereafter, the results of the production phase are presented considering an energy allocation perspective, whereas results considering economic and mass allocations can be found in tables SM21 – SM24 in the SM. Finally, the total results considering transport to port of destination (i.e., exports abroad) are included.

3.1. Life cycle inventory

3.1.1. Fishing phase

Data on fishing activities were classified based on the fleet of origin (i.e., Austral-owned, or third-party vessels). Company-owned vessels represent the highest percentage of landings, except in Ilo, where third-party vessels contribute overwhelmingly to *E. ringens* landings (Table 1). However, it should be noted that no geographical location of where the *E. ringens* were caught was provided, but rather monthly bulk landings per vessel (Table 2).

Table 2 presents the annual fuel consumption and *E. ringens* landings for company-owned vessels. With this information, the fleet's fuel use intensity (FUI), a ratio that represents the amount of diesel needed to catch 1 t of *E. ringens* and widely used in fisheries LCA studies as a proxy for fishing effort and energy intensity (Ruiz-Salmón et al., 2021) can be calculated. In the case of third-party vessels, monthly fuel consumption and *E. ringens* landings at the *chatas* were gathered. In 2019, 105 vessels from the third-party fleet landed over 100,000 t of *E. ringens*, using over 3 million l of diesel. Similarly, in 2021, 122 third-party vessels landed over 193,000 t with a total diesel consumption of roughly 3.7 million l. In addition, hull maintenance was modeled for company-owned vessels based on naval steel panel replacement reported by the company. Hence, it was calculated that approximately 198 mg of naval steel is added to the vessels for maintenance per kilogram of landed catch. Additionally, lubricant consumption added up to 634 and 519 mg per kg of fish landed for 2019 and 2021, respectively. Considering that data on maintenance were not available for third-party vessels it was considered that they had the same maintenance work as the company's fleet.

Table 1
Weight contribution of landed catch according to each fleet, per plant for 2019 and 2021.

Year	Plants	Own vessels	Third party fleet
2019	Coishco	66 %	34 %
	Chancay	71 %	29 %
	Pisco	98 %	2 %
	Ilo	10 %	90 %
	All plants	65 %	35 %
2021	Coishco	71 %	29 %
	Chancay	89 %	11 %
	Pisco	94 %	6 %
	Ilo	3 %	97 %
	All plants	61 %	39 %

Table 2
Fuel consumption and *anchoveta* (*Engraulis ringens*) landings for fishmeal and fish oil (FMFO) production by Austral-owned vessels in 2019 and 2021.

Vessel	2019		2021	
	Fuel use (l)	Landed *E. ringens* (t)	Fuel use (l)	Landed *E. ringens* (t)
V1	247,963	9408	328,233	12,332
V2	203,295	11,267	329,615	19,487
V3	837,859	17,426	1,042,328	26,525
V4	312,637	11,560	310,214	12,485
V5	270,070	10,071	170,987	11,053
V6	198,469	6711	376,497	15,343
V7	375,880	11,176	462,501	13,020
V8	399,872	8974	609,534	14,740
V9	98,799	1899	936,340	19,427
V10	646,510	13,541	656,390	21,350
V11	565,165	11,282	693,109	18,574
V12	429,216	11,739	246,998	15,490
V13	472,684	12,192	618,188	20,214
V14	341,815	10,243	465,227	17,119
V15	392,415	9365	511,882	12,454
V16	211,585	7745	325,205	12,665
V17	170,836	7311	592,625	16,939
V18	254,304	11,019	293,218	14,008
V19	357,721	10,517	489,264	14,612
V20	482,072	10,835	550,607	15,535
Total	**7,269,168**	**204,281**	**10,008,961**	**323,372**
$\bar{x}$ (SD)	**363,458 (±173,010)**	**10,214 (±2952)**	**500,448 (±216,981)**	**16,169 (±3745)**

In terms of cooling, there are 12 vessels owned by the company with a refrigerated seawater (RSW) system. This system uses anhydrous ammonia gas (NH_3) as a refrigerant, which is refilled every 5 years. Moreover, all company-owned vessels have a cooling system for food storage, which uses 4 kg of R134A, and is refilled every two years, at a rate of 2 kg of R134A per maintenance service. Additionally, 979 gal (1 gal = 3.79 l) of ELC 238–8650 coolant were used in 2019 and 1453 in 2021 for the diesel engines. Further data on oils and lubricants used during fishing can be found in Table SM1 in the SM.

Fishing equipment was estimated at 43 t per vessel. During fishing operations, approximately 6.6 % of the mass weight of the gear is expected to be emitted into the water due to gear wear and tear (Richardson et al., 2019). Although the weights of the third fleet's fishing nets are not available, plastic emissions due to wear and tear of fishing nets can be estimated considering plastic emission factors per t of fish landed (Deville et al., 2023).

Currently, most antifouling paints used on boat hulls have a solid proportion of alkyd plastic that improves the antifouling properties of the paints. The company's fleet uses an average of 104 gal of antifouling paint, applied each time they undergo maintenance (approximately every 2 years). However, there is no information on the amount of paint applied to third party vessels; hence, the emission factor of plastic polymers in antifouling paint per t of fish unloaded were used to estimate its release to the ocean (Deville et al., 2023). Table 3 presents the inventory data for the provision of 1 t of *E. ringens* for reduction into

Table 3
Life cycle inventory (LCI) data for the provision of 1 t of *E. ringens*. Weighted average of the years 2019 and 2021.

Inputs	Material/fuel	Unit	
Inputs			
	Alkyd paint	g	1.28E+01
	Copper	g	9.44E+00
	Lead	g	2.98E+01
	Aluminum alloy	g	9.46E-02
	Cast iron	g	6.15E+00
	Steel (engine)	g	1.76E+01
	Steel (hull)	g	2.17E+02
	Nylon	g	1.86E+03
	LDPE	g	3.37E+00
	Refrigerant R134a	g	2.02E-01
	Diesel	MJ	1.09E+03
Outputs			
	E. ringens	t	1.00E+00
	HFC-134a (air)	g	4.05E-02
	Nylon (ocean)	g	3.25E+02
	Alkyd polymer (ocean)	g	7.81E-01

FMFO products.

3.1.2. Transformation phase

Reduction occurs once the biomass is pumped through pipes from the *chata* into the processing plant. Thereafter, a cooking, pressing, decanting, and drying process begins (Glencross et al., 2024). The plant at Coishco has the highest processing capacity, thus it received ~50 % of the total landing in the years under assessment (Table 4).

A total of 320,187 t of *E. ringens* were landed at the plants in 2019, whereas in 2021 landings were 62 % higher (i.e., 517,192), with increases homogeneous across the 4 plants. The ratio between total catch and fishmeal production was relatively stable across the plants, ranging between 4.15 in Pisco for the year 2019 to 4.45 in Ilo in the same year. The weighted average ratio was 4.21 in 2019 and 4.23 in 2021. The ratio between catch and fish oil, in contrast, was more volatile between plants and for the different years, ranging from 22.72 in Coishco in 2019 to 90.41 in Ilo in that same year (see Table 4). The low oil production in Ilo in 2019 is mainly due to the low-fat content in the captured *E. ringens* in Ilo for that season (2.7 %), compared to Coishco and Chancay (both 5.2 %), and Pisco (4.2 %). Despite these apparent disparities, the ranges are within those reported by the Marine Ingredients Organisation (i.e., IFFO) and the scientific literature (Péron et al., 2010; Shepherd and Jackson, 2013). Considering the production information reported in Table 4, the energy allocation values from Fréon et al. (2017) and the market value of FMFO (Banco Central de Reserva del Perú, 2023a; 2023b); energy, economic and mass allocation were developed for each plant and year (see Table 5).

Energy use at the plant is destined mainly for cooking, pressing, decanting, and drying processes. For these, natural gas and diesel are the main fuels used, except at Ilo where residual fuel oil (R6) remains the main energy carrier (see Table 6). In contrast, electricity from the national grid is mainly used in the transportation of raw materials between the different stages of transformation and other processes that do not use thermal energy (e.g., pumping of raw materials, cooling, packaging). The energy content of the various fuels used was obtained from the Peruvian National Greenhouse Gas Inventory (MINAM, 2020, 2021) and the electricity mix was modeled based on the indications in (Vázquez-Rowe et al., 2015).

Table 5
Energy, economic and mass allocation for fishmeal and fish oil (FMFO) production per year of assessment.

Year	Plant	Allocation	Fishmeal	DHC Fish oil	IHC Fish oil
2019	Coishco	Energy	34.0 %	57.3 %	8.7 %
		Economic	77.4 %	22.6 %	
		Mass	84.5 %	13.5 %	2.0 %
	Chancay	Energy	34.0 %	53.0 %	13.0 %
		Economic	81.2 %	18.8 %	
		Mass	87.3 %	10.2 %	2.5 %
	Pisco	Energy	34.0 %	57.7 %	8.3 %
		Economic	84.9 %	15.1 %	
		Mass	89.9 %	8.8 %	1.3 %
	Ilo	Energy	34.0 %	60.7 %	5.3 %
		Economic	92.7 %	7.3 %	
		Mass	95.3 %	4.3 %	0.4 %
2021	Coishco	Energy	34.0 %	58.0 %	8.0 %
		Economic	81.5 %	18.5 %	
		Mass	87.4 %	11.1 %	1.5 %
	Chancay	Energy	34.0 %	57.7 %	8.3 %
		Economic	83.1 %	16.9 %	
		Mass	88.6 %	10.0 %	1.4 %
	Pisco	Energy	34.0 %	58.0 %	8.0 %
		Economic	83.5 %	16.5 %	
		Mass	88.8 %	9.8 %	1.4 %
	Ilo	Energy	34.0 %	60.1 %	5.9 %
		Economy	86.2 %	13.8 %	
		Mass	90.8 %	8.4 %	0.8 %

DHC: Direct human consumption, IHC: Indirect human consumption.

Beyond the energy requirements of the plants, the reduction industry uses a wide variety of inputs for its processes, ranging from acetic acid used for the landed *E. ringens* preservation, to ethoxyquin (antioxidant) and pH regulators. It is worth noticing that the plants at Coishco and Chancay use mainly butylhydroxytoluene (BHT) and butylhydroxyanisole (BHA) as antioxidants for fishmeal production, while Pisco and Ilo plants mainly use ethoxyquin. These inputs can be seen in Tables SM3-SM6 in the SM. Road freighting of these inputs to the plants, as well as waste flows to waste management sites, were also modeled. Given that data regarding the characteristics of the lorries were lacking, information of the Peruvian vehicle fleet was obtained from CAN (2015). Tables SM7-SM10 in the SM present the tonne-kilometers (i.e., tkm) related to the transportation of materials. Similarly, Tables SM11-SM14 in the SM present the tkms generated by the transportation of waste generated in all plants. Waste production was highest in Coishco in 2021 (1249 t) and lowest for Pisco in 2019 (33 t). However, it should be noted that solid waste treatment and its subsequent emissions have not been included in the analysis. Table 7 presents the inventory for the production of 1 t of fishmeal and 1 t of fish oil.

Table 4
Landed catch and fishmeal and fish oil (FMFO) production per plant for the years under assessment.

Year	Plant	Landed catch (t)	Fishmeal (t)	DHC fish oil (t)	IHC fish oil (t)	Catch / fishmeal	Catch / fish oil
2019	Coishco	164,528	39,404	6292	949	4.18	22.72
	Chancay	44,204	10,587	1233	302	4.18	28.79
	Pisco	65,435	15,759	1544	222	4.15	37.04
	Ilo	46,020	10,332	468	41	4.45	90.41
2021	Coishco	248,813	59,597	7544	1034	4.17	29.00
	Chancay	79,318	18,763	2116	305	4.23	32.76
	Pisco	74,477	17,636	1946	269	4.22	33.63
	Ilo	114,584	26,169	2416	239	4.38	43.16

DHC: Direct human consumption, IHC: Indirect human consumption.

Table 6
Energy requirements of the fishmeal and fish oil (FMFO) reduction plants (i.e., Coishco, Chancay, Pisco and Ilo) for years 2019 and 2021. For data in volume refer to Table SM2 in the Supplementary Material (SM).

Energy source		Unit	2019				2021			
			Chancay	Coishco	Pisco	Ilo	Chancay	Coishco	Pisco	Ilo
Diesel B5	Transport vehicles	GJ	217	537	427	139	97	1018	283	274
	Plant equipment	GJ	–	53,883	–	–	–	117,248	1711	–
	Mobile equipment	GJ	174	481	173	35	–	656	20	38
Residual fuel oil (R500)	Plant equipment	GJ	2093	–	–	–	9846	–	–	–
Natural gas	Plant equipment	GJ	94,152	140,434	105,351	–	106,116	122,672	121,190	–
Propane	Mobile equipment	GJ	1263	3626	279	–	2295	3970	141	–
Residual fuel oil (R6)	Plant equipment	GJ	–	–	–	75,905	–	–	–	185,104
Electricity	Energy from the grid	kWh	1,589,620	6,171,665	3,267,845	1,203,415	2,743,981	7,660,542	3,547,922	3,062,304
Diesel B5	Generators	GJ	4116	2479	1470	3866	16	120,062	725	801
Total		**GJ**	**107,738**	**223,658**	**123,739**	**84,277**	**128,250**	**393,289**	**136,842**	**197,242**
Energy / landed catch		***MJ / t***	***1673***	***1295***	***1891***	***1831***	***1658***	***1552***	***1837***	***1721***

Table 7
Life cycle inventory (LCI) data for the production of 1 t of fishmeal and 1 t of fish oil. Weighted average of the years 2019 and 2021. Reported using energy allocation.

	Material/fuel	Unit	Fishmeal	Fish oil
Inputs				
	E. ringens	t	1.44E+00	2.05E+01
	Polyacrylamide	kg	2.42E-01	3.47E+00
	Phosphoric Acid	kg	3.60E-01	5.15E+00
	Acetic Acid	kg	4.04E-01	5.77E+00
	Sodium hydroxide	kg	5.34E-01	7.64E+00
	Formic Acid	kg	2.44E-03	3.49E-02
	Nitric Acid	kg	7.43E-02	1.06E+00
	Iron Sulfate	kg	3.79E+00	5.42E+01
	Alcohol	kg	2.62E-02	3.75E-01
	Salt	kg	7.37E-01	1.05E+01
	Lime	kg	5.22E-02	7.46E-01
	Morpholine	kg	1.75E-03	2.50E-02
	Dimethylaminopropylamine	kg	1.88E-04	2.69E-03
	Monoethanolamine	kg	3.76E-04	5.37E-03
	Diethanolamine	kg	1.25E-05	1.78E-04
	Sodium sulfite	kg	1.05E-02	1.51E-01
	Propylene glycol	kg	2.78E-03	3.98E-02
	Electricity	kWh	5.02E+01	7.17E+02
	Diesel B5	GJ	5.33E-01	7.62E+00
	Natural Gas	GJ	1.18E+00	1.69E+01
	Propane	GJ	1.98E-02	2.84E-01
	Residual 500	GJ	2.05E-02	2.93E-01
	Residual 6	GJ	4.48E-01	6.40E+00
	Polypropylene	kg	3.19E+00	–
	Synthetic fiber	kg	2.27E-02	–
	Citric Acid	kg	2.85E-02	–
	Sunflower oil	kg	1.07E+00	–
	Ethoxyquin	kg	4.40E-01	–
	Butylhydroxytoluene	kg	5.57E-01	–
	Butylhydroxyanisole	kg	8.56E-02	–
Outputs				
	Fishmeal	t	1.00E+00	–
	Fish oil	t	–	1.00E+00
	Water (air)	m^3	1.49E-03	2.13E-02
	Particulates <2.5 μm	kg	8.70E-05	1.24E-03
	Nitrogen oxides (air)	kg	1.62E-02	2.31E-01
	Carbon monoxide, fossil (air)	kg	2.27E-02	2.27E-02
	Sulfur dioxide (air)	kg	3.65E-03	5.21E-02
	*BOD_5 (ocean)	kg	8.65E-02	1.24E+00
	COD (ocean)	kg	1.56E-01	2.22E+00
	DOC (ocean)	kg	5.90E-02	8.44E-01
	Oils, biogenic (ocean)	kg	5.05E-04	7.21E-03
	Suspended solids (ocean)	kg	8.82E-03	1.26E-01
	TOC (ocean)	kg	4.49E-02	6.42E-01

* Amount of dissolved oxygen needed (in kg) by aerobic biological organisms to break down organic material present in residual waters over a 5-day period at 20 °C (Kosseva, 2020).

3.1.3. FMFO freighting

Data on FMFO freighting and the packaging used were obtained directly from Austral Group S.A.A., as well as data on vehicles, distance traveled, and weight carried. The modeling of FMFO transport was carried out considering all the products sold during the years 2019 and 2021. Details of the land transportation of FMFO are shown in Tables SM15 and SM16. Road transportation of the fishmeal is carried out using 50 kg polypropylene woven bags and/or big bags (1200 kg), while fish oil is transported in tankers specialized for transporting oily substances.

FMFO transport has been considered in two stages. First, road transportation from the plant to the port of departure. The second phase includes maritime freighting from the port of departure in Peru to the port of destination abroad. Ground transportation between the port of destination and final consumer is not included. In contrast to the information on the transportation of inputs and waste, the transportation of finished products does have detailed data on engine type and their distribution in the vehicle fleet used by the company. In the case of transportation of final products, all trips were modeled considering a 32-t diesel truck.

Marine transport considers only two types of transport: container ships and bulk carriers. For container ship transport, in the case of fishmeal, the bags are placed directly into containers. In contrast, for fish oil a special packaging, called a flexibag, is placed inside the container and filled with oil until it is limited by the container. In the case of bulk carriers, for fishmeal, the bags transported to the port are opened and poured directly into the cargo hold. In contrast, fish oil is pumped directly to the cargo hold.

A pattern is evident in terms of vessel preferences for maritime transport according to destination. The two regions that purchase the most FMFO from the company are China (the main buyer of fishmeal), followed by Europe (main buyer of fish oil). Europe has a marked preference for transport in bulk vessels (ca. 95 %), whereas China imports all FMFO in containers. Data linked to ocean freighting are shown in Tables SM17-SM18. In addition, to reach Europe and China, regions that purchase over 70 % of their products in weight, it takes on average 12,600 and 22,400 km of maritime transport, respectively. Overall, for fishmeal, there is a marked preference for container ships (97 % in 2019 and 91 % in 2021). For fish oil, there is an overall preference for bulk carriers.

3.2. Life cycle impact assessment

3.2.1. Environmental impact results in the fishing phase

FUI values for the *E. ringens* fleet assessed ranged from 32.2 l/t in 2019 to 26.8 l/t in 2021. This improvement in fuel consumption efficiency between both years is mainly due to an increase in available quota (i.e., the total allowable catch per vessel per fishing season) in 2021 as compared to 2019, which has been shown to be a critical influence regarding the energy efficiency of fishing fleets (Ziegler and Hornborg, 2014). When disaggregating the results, FUI values were higher for the company-owned fleet (i.e., 35.6 l/t in 2019 and 31.0 l/t in 2021, 13 % less), whereas for the third-party vessels values decreased at a higher rate (i.e., −31 %) from 28.7 l/t in 2019 to 19.8 l/t in 2021. Fig. 3 presents a box-plot graph of both fleets' FUI and the total weighted average for both years.

Fuel use for propelling and fishing activities has shown to be the main carrier (ca. 80 % in the case of GHG emissions) of environmental impacts in industrial fishing fleets throughout the world (Parker et al., 2018). The results from this study (see Table 8) confirm these results for most impact categories, except for marine ecotoxicity, human toxicity and marine eutrophication, which are mainly affected by antifouling emissions and the vesselś construction and maintenance. In terms of GHG emissions, on average, the impact of landing 1 t of *E. ringens* was 109.1 kg CO_2eq in 2019 and 88.1 kg CO_2eq in 2021, 19 % lower. Overall, the total impacts in terms of GHG emissions are mainly linked to fuel combustion (96 %) and vessel maintenance (1 %). In contrast, for marine ecotoxicity, antifouling emissions during the fishing activity contributed over 99 % of the total. Furthermore, vessel construction and maintenance contributed to 63 % of total impacts in the freshwater ecotoxicity category.

3.2.2. Environmental impact in the transformation phase

Fuel consumption is the single-most dominant activity in terms of environmental impacts in the transformation phase, although the use of chemicals and electricity is relevant in several impact categories. For instance, in the case of fishmeal, the impacts related to the production of chemicals used in the formulation, mainly antioxidants (i.e., ethoxyquin) and phosphoric acid, are dominant in freshwater ecotoxicity (67 %), marine eutrophication (90 %) and land use (86 %), considering the 2019 and 2021 weighted average. Electricity use is a relevant contributor to environmental burdens for freshwater (28 %) and marine (22 %) ecotoxicity.

Regarding GHG emissions, the transformation of *E. ringens* into 1 t of fishmeal generated on average 196 kg CO_2eq, whereas 2650 kg CO_2eq for fish oil. In the case of fishmeal, combustion of fossil fuels (i.e., natural gas, diesel, Residual Fuel Oil No. 6 and Residual 500) is the main contributor to global warming (88 %), followed by electricity, plastic bags and chemicals, with 3 % each. Similarly, for fish oil, fuel use contributed to 93 % of all the GHG emissions, followed by electricity (4 %) and chemicals (2 %).

3.2.3. Environmental impacts of the production stage

The environmental impacts during the production phase of FMFO (i.e., combined impact of fishing and transformation) are, as expected, dominated by the fishing stage and fuel consumption for heat during the transformation process. Table 9 presents the results of all impact categories of fishmeal and fish oil. The results are presented as the weighted average for both years, considering energy allocation. Results regarding the environmental impacts produced per year, considering energy, mass and economic allocations are shown in tables SM19-SM24 in the SM. The main driver of environmental impacts is related to the burning of diesel during fishing. Nonetheless, fuel use during the transformation processes, mainly natural gas combustion, except for the plant at Ilo, which relies heavily Residual Fuel Oil No.6, is the leading activity in global warming, ozone depletion, and terrestrial and freshwater ecotoxicity during the production phase.

In terms of GHG emissions, fuel use during the transformation process presents the highest contribution, up to 57 % for fishmeal and ranging between 52 % and 58 % for fish oil in the production phase. The fishing stage is the second activity that contributes the most to GHG emissions, varying between 31 % and 49 % in 2019 and between 26 % and 44 % in 2021, depending on the plant. It should be noted that for Coishco, in 2019, the fishing stage was the main contributor to GHG emissions, while, in 2021, the transformation stage was the largest emitter. This is mainly due to a reduction in the energy efficiency of the process at Coishco and a 17 % reduction in the FUI during fishing between 2019 and 2021.

An uncertainty analysis was conducted using MC simulation to produce FMFO in 2019 in Coishco. The mean result obtained was 292 ± 27 kg CO_2eq per t of fishmeal and 4965 ± 481 kg per t of fish oil. It must be noted that this uncertainty is linked to the quality of the data, in which a relatively high amount of primary data were available for the foreground system. In fact, this uncertainty shows a lower range of values as compared to the variability between the different plants.

The fishing stage accounts for >99 % of marine ecotoxicity impacts for both products due to the emisssions of antifouling paint particles to the ocean. Moroever, based on antifouling emission factors, it is estimated that the *E. ringens* provision in 2019 and 2021 emitted 250 and 404 kg of alkyd plastic polymers in the form of microplastics, respectively. Additionally, approximately 119 and 193 t of fishing gear, mainly nylon, were emitted in 2019 and 2021 respectively. Efforts are being released to include impact pathways to calculate the environmental damage related to these plastic emissions (Woods et al., 2021), although

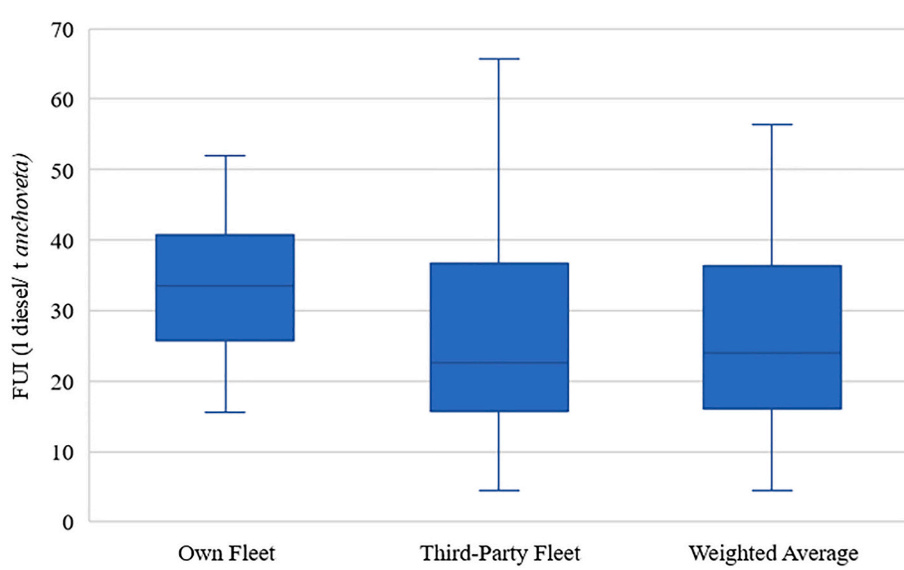

Fig. 3. Box plot figure of the fuel use intensity (FUI) of company-owned and third-party fleets, and the total weighted average for both study years (i.e., years 2019 and 2021).

Table 8
Weighted average characterization environmental impact results at the midpoint level of the provision of 1 t of landed anchoveta for the years 2019 and 2021.

Impact category	Unit	Total	Lubricating & mineral oils	Vessel C&M	Refrigerant R134a	Diesel combustion	Antifouling emissions
Global warming	kg CO_2eq	9.61E+01	8.54E-01	1.75E+00	3.35E-03	9.32E+01	–
Stratospheric ozone depletion	kg CFC11eq	2.51E-05	5.60E-07	1.37E-06	1.34E-07	2.31E-05	–
Ionizing radiation	kBq Co-60 eq	9.04E-01	4.22E-02	3.55E-02	8.46E-05	8.26E-01	–
Ozone formation, Human health	kg NO_xeq	2.08E+00	4.12E-03	3.81E-03	4.47E-06	2.07E+00	–
Fine particulate matter formation	kg PM2.5 eq	6.66E-01	1.51E-03	2.96E-03	3.31E-06	6.62E-01	–
Ozone formation, Terrestrial ecosystems	kg NO_xeq	2.09E+00	5.42E-03	3.96E-03	4.88E-06	2.08E+00	–
Terrestrial acidification	kg SO_2eq	2.11E+00	3.61E-03	7.66E-03	8.01E-06	2.10E+00	–
Freshwater eutrophication	kg Peq	1.55E-02	4.43E-04	3.15E-03	5.27E-07	1.19E-02	–
Marine eutrophication	kg Neq	7.18E-04	1.37E-05	6.05E-04	3.86E-08	9.96E-05	–
Terrestrial ecotoxicity	kg 1,4-DCB	1.07E+02	3.22E+00	2.37E+01	1.19E-02	8.05E+01	4.16E-15
Freshwater ecotoxicity	kg 1,4-DCB	4.76E-01	3.20E-02	3.02E-01	1.31E-04	1.42E-01	1.90E-20
Marine ecotoxicity	kg 1,4-DCB	4.54E+02	4.33E-02	3.92E-01	1.71E-04	2.85E-01	4.54E+02
Human carcinogenic toxicity	kg 1,4-DCB	1.27E+00	4.18E-02	6.42E-01	1.03E-04	5.86E-01	1.68E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	5.38E+01	6.98E-01	1.42E+01	2.48E-03	4.94E+00	3.39E+01
Land use	m^2a crop eq	1.33E+00	3.42E-02	5.38E-02	2.67E-05	1.24E+00	–
Mineral resource scarcity	kg Cu eq	7.01E-02	2.93E-03	4.26E-02	8.38E-06	2.46E-02	–
Fossil resource scarcity	kg oil eq	3.09E+01	7.30E-01	5.05E-01	4.19E-04	2.97E+01	–
Water consumption	m^3	7.55E-02	6.04E-03	3.78E-02	2.61E-05	3.16E-02	–

C & M: Construction and Maintenance

Table 9
Weighted averge characterization environmental impact results at the midpoint level of the production of 1 t of fishmeal and fish oil for years 2019 and 2021. Results reported using an energy allocation.

				Fishing Stage	Transformation stage				
Product	Impact Category	Unit	Total Production	Total	Total	Fuel Use	Electricity	Chemicals	Plastic bags
Fishmeal									
	Global warming	kg CO_2eq	3.19E+02	1.20E+02	1.99E+02	1.75E+02	8.62E+00	7.58E+00	7.54E+00
	Stratospheric ozone depletion	kg CFC-11 eq	1.10E-04	3.26E-05	7.79E-05	5.60E-05	4.98E-06	1.59E-05	1.01E-06
	Ionizing radiation	kBq Co-60 eq	2.78E+00	1.18E+00	1.60E+00	1.08E+00	3.16E-02	3.33E-01	1.54E-01
	Ozone formation, Human health	kg NO_xeq	3.22E+00	2.67E+00	5.44E-01	4.97E-01	1.19E-02	1.95E-02	1.55E-02
	Fine particulate matter formation	kg PM2.5 eq	1.08E+00	8.57E-01	2.27E-01	2.03E-01	3.50E-03	1.30E-02	7.80E-03
	Ozone formation, Terrestrial ecosystems	kg NO_xeq	3.24E+00	2.69E+00	5.56E-01	5.07E-01	1.23E-02	2.03E-02	1.64E-02
	Terrestrial acidification	kg SO_2eq	3.29E+00	2.72E+00	5.71E-01	5.07E-01	9.76E-03	3.36E-02	2.03E-02
	Freshwater eutrophication	kg Peq	3.73E-02	2.05E-02	1.68E-02	1.15E-02	4.11E-04	3.27E-03	1.60E-03
	Marine eutrophication	kg Neq	6.32E-03	1.02E-03	5.30E-03	3.60E-04	4.05E-05	4.79E-03	1.13E-04
	Terrestrial ecotoxicity	kg 1,4-DCB	7.27E+02	1.43E+02	5.84E+02	5.11E+02	1.06E+01	4.79E+01	1.48E+01
	Freshwater ecotoxicity	kg 1,4-DCB	3.41E+00	6.66E-01	2.74E+00	4.44E-01	2.60E-01	1.87E+00	1.66E-01
	Marine ecotoxicity	kg 1,4-DCB	6.55E+02	6.53E+02	2.18E+00	9.20E-01	3.24E-01	7.10E-01	2.22E-01
	Human carcinogenic toxicity	kg 1,4-DCB	4.15E+00	1.74E+00	2.41E+00	1.32E+00	1.76E-01	6.35E-01	2.76E-01
	Human non-carcinogenic toxicity	kg 1,4-DCB	1.07E+02	7.66E+01	3.02E+01	1.51E+01	2.09E+00	9.22E+00	3.69E+00
	Land use	m^2a crop eq	1.32E+01	1.73E+00	1.15E+01	1.36E+00	2.04E-01	9.82E+00	6.81E-02
	Mineral resource scarcity	kg Cu eq	2.12E-01	9.73E-02	1.15E-01	5.00E-02	1.02E-02	3.99E-02	1.48E-02
	Fossil resource scarcity	kg oil eq	1.10E+02	4.00E+01	7.01E+01	5.84E+01	3.16E+00	3.10E+00	5.46E+00
	Water consumption	m^3	4.48E+00	1.04E-01	4.37E+00	3.07E-01	3.85E+00	1.52E-01	6.68E-02
Fish oil									
	Global warming	kg CO_2eq	4.44E+03	1.78E+03	2.66E+03	2.47E+03	1.36E+02	5.66E+01	–
	Stratospheric ozone depletion	kg CFC-11 eq	1.42E-03	4.66E-04	9.51E-04	7.97E-04	8.10E-05	7.27E-05	–
	Ionizing radiation	kBq Co-60 eq	3.64E+01	1.68E+01	1.96E+01	1.54E+01	5.09E-01	3.63E+00	–
	Ozone formation, Human health	kg NO_xeq	4.56E+01	3.82E+01	7.44E+00	7.10E+00	1.93E-01	1.50E-01	–
	Fine particulate matter formation	kg PM2.5 eq	1.53E+01	1.23E+01	3.07E+00	2.89E+00	5.64E-02	1.25E-01	–
	Ozone formation, Terrestrial ecosystems	kg NO_xeq	4.60E+01	3.84E+01	7.59E+00	7.23E+00	1.99E-01	1.54E-01	–
	Terrestrial acidification	kg SO_2eq	4.65E+01	3.88E+01	7.70E+00	7.24E+00	1.57E-01	2.97E-01	–
	Freshwater eutrophication	kg Peq	4.99E-01	2.93E-01	2.05E-01	1.65E-01	6.64E-03	3.40E-02	–
	Marine eutrophication	kg Neq	3.01E-02	1.46E-02	1.56E-02	5.13E-03	6.57E-04	9.77E-03	–
	Terrestrial ecotoxicity	kg 1,4-DCB	9.96E+03	2.04E+03	7.92E+03	7.30E+03	1.72E+02	4.46E+02	–
	Freshwater ecotoxicity	kg 1,4-DCB	2.47E+01	9.52E+00	1.52E+01	6.18E+00	4.22E+00	4.77E+00	–
	Marine ecotoxicity	kg 1,4-DCB	9.35E+03	9.33E+03	2.45E+01	1.29E+01	5.27E+00	6.30E+00	–
	Human carcinogenic toxicity	kg 1,4-DCB	5.43E+01	2.49E+01	2.94E+01	1.88E+01	2.85E+00	7.81E+00	–
	Human non-carcinogenic toxicity	kg 1,4-DCB	1.44E+03	1.09E+03	3.44E+02	2.15E+02	3.39E+01	9.53E+01	–
	Land use	m^2a crop eq	5.02E+01	2.47E+01	2.56E+01	1.93E+01	3.36E+00	2.86E+00	–
	Mineral resource scarcity	kg Cu eq	2.76E+00	1.39E+00	1.36E+00	7.08E-01	1.65E-01	4.92E-01	–
	Fossil resource scarcity	kg oil eq	1.48E+03	5.72E+02	9.04E+02	8.32E+02	5.13E+01	2.02E+01	–
	Water consumption	m^3	6.71E+01	1.49E+00	6.56E+01	1.81E+00	6.26E+01	1.24E+00	–

these were not considered within the scope of the current study.

When analyzing the results at the endpoint level, fishing contributed to 66 % of the total impacts in the case of fishmeal production and 68 % for fish oil (see Table SM25 in the SM). Furthermore, human health was the dominant endpoint for all plants, averaging 94 % of the total single score, mainly due to particulate matter formation and global warming.

In the case of fishmeal, the fishing phase contributed to 66 % of the human health related impacts (52 % due to particulate matter formation, and 11 % due to global warming) and the transformation phase 34 % (12 % due to particulate matter formation, and 20 % due to global warming). Similarly, for fish oil, fishing amounted to 68 % of the total impacts on human health (54 % from particulate matter formation, and 12 % due to global warming) whereas the transformation processes contributed to 32 % (11 % from particulate matter formation, and 19 % due to global warming). Fig. 4 illustrates the 2019 and 2021 weighted average distribution of environmental impacts at the endpoint level to produce 1 t of fishmeal in the four plants. Figures SM2-SM5 in the SM illustrate the impacts at the endpoint levels of FMFO production for 2019 and 2021 for all the plants analyzed.

3.2.4. Total environmental impacts of FMFO production and transport

When considering an energy allocation, total freighting (road and maritime transport) is the main driver of environmental impacts for fishmeal. In contrast, for fish oil, transport is the least relevant activity in terms of environmental burdens. The transport of FMFO to the final port of destination shows important contributions to environmental impacts (Fig. 5).

In terms of GHG emissions, the fishmeal transport to China produces an average emission of 239 kg CO_2eq per t, contributing up to 42 % of the total (production and transport) when considering an energy allocation (36 % sea freight and 6 % road transport). In contrast, the transport of fish oil to Europe amounted to 103 kg CO_2eq per t contributing only to 3 % of the total GHG emissions when considering an energy allocation. Table SM26 presents the ReCiPe midpoint impacts of the FMFO road and maritime transportation.

Fishmeal transport amounts to over 50 % of the impacts related to ozone formation, human toxicity, fine particulate matter formation, ozone depletion and terrestrial acidification. In addition, fishmeal road transport to the Callao port is the dominant activity for terrestrial ecotoxicity, amounting to 40 % on average (Fig. 5).

It is important to highlight that the antifouling emissions to the ocean during fishing continues to dominate the marine ecotoxicity category. Although it is expected that the shipping vessels emit a similar or higher amount of antifouling into the ocean mainly due to their bigger size and travel distance, we do not possess information regarding merchant antifouling emissions outside of the Peruvian EEZ, constituting a limitation of our modeling.

Total impacts at an endpoint level show that human health impacts represent ca. 95 % of environmental burdens, with marine freight representing 52 % of impacts, followed by fishing (32 %) and transformation (16 %), when considering an energy allocation. In contrast, for fish oil, fishing has the largest contribution, 63 %, followed by transformation (34 %) and transport (3 %). Figures SM6-SM9 in SM illustrate the impacts at the endpoint level of FMFO production and transport of each plant for the years 2019 and 2021.

4. Discussion

4.1. *E. ringens* fishing phase

The Peruvian *E. ringens* fishery for FMFO production has shown to be the one of the most efficient industrial fisheries in the world based on the current study and Avadí et al. (2014), and previous studies of fisheries in different regions worldwide (i.e. Parker et al., 2018; Vázquez-Rowe et al., 2010; Laso et al., 2018). Yet, recent FUI data for the Peruvian *E. ringens* fishery were not available in the scientific literature, which added to the fact that recent studies have suggested that *E. ringens* stocks in Peru have been dwindling throughout the 21st century (IFFO, 2009). However, the data obtained in this study remain within similar ranges of FUI as those reported by Avadí et al. (2014), that also studied the Peruvian *E. ringens* fishery (see Table 10). More specifically, the company-owned vessels fall within the upper range of FUI values reported by Avadí et al. (2014), whereas third-party vessels show mid-range values.

Although the direct comparison of these results (i.e., Avadí et al., 2014 and the current study) may suggest a slight increase in FUI, this assessment must be taken with caution. Methodological factors, especially in terms of data collection, and the fact that the comparison is between a sample of the whole Peruvian fishing vessels in Avadí et al. (2014) versus the fishing fleet of a single company in our study, suggests that this type of conclusion may be misleading. In fact, a portion of the LCIs of the fleet sections reported by Avadí et al. (2014) are obtained through linear regressions, and not directly, whereas in the present study all data are primary. Therefore, considering the differing methods in these studies, it is prudent to affirm that FUI obtained are in similar ranges to those obtained by Avadí et al. (2014).

The gap in the temporality of the data extends to global reduction fisheries, with most of the available studies referring to data collected at least a decade ago. One of the most extensive studies is that of Parker et al. (2018), in which they analyze and compare an important proportion of the world's fisheries, using data from 2011. On a global average, the FUI of FMFO fisheries reported by Parker et al. (2018) is 82

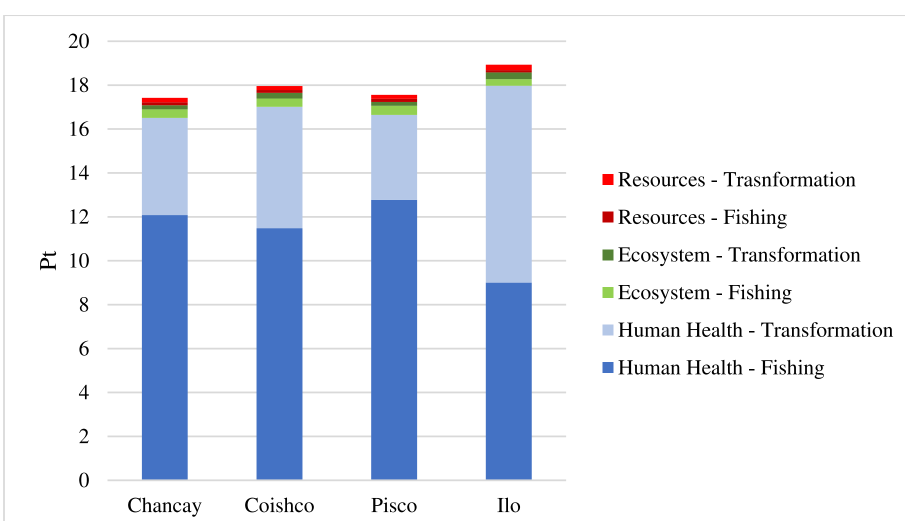

Fig. 4. Fishmeal production impacts of each plant at the endpoint level using ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/A single score method assuming energy allocation. Results are presented as a weighted average of the years 2019 and 2021.

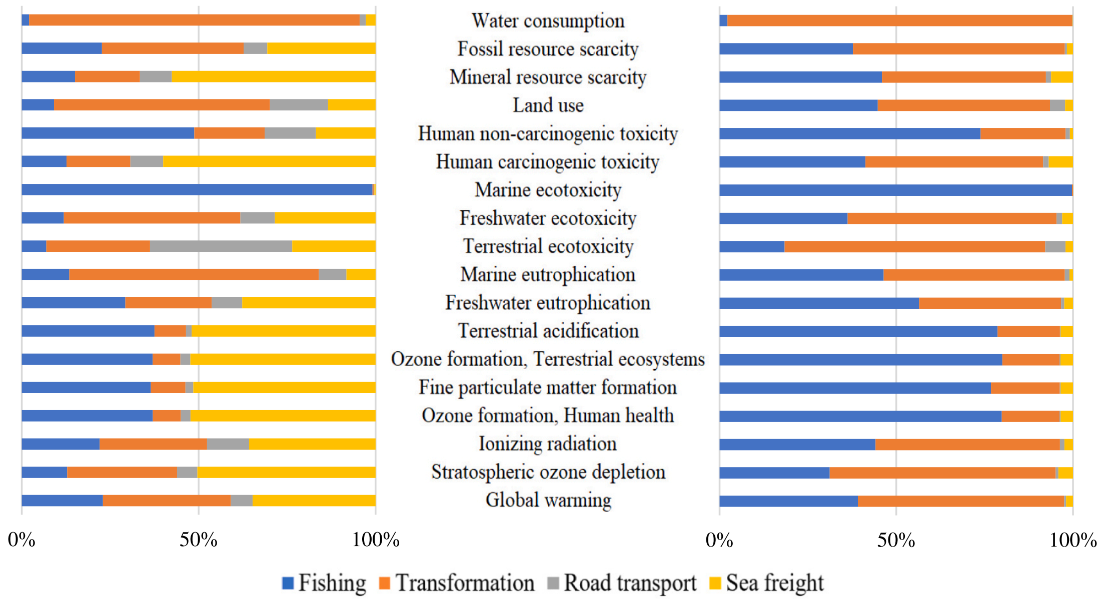

Fig. 5. Weighted average relative midpoint environmental impacts of the production and transport (to worldwide destinations) considering an energy allocation per FU. **Left:** Fishmeal. **Right:** Fish oil.

Table 10
Fuel use intensty (FUI) of the Austral-owned vessel and third party fleet in this study, as compared to other datpoints available in the international scientific literature.

Species	Country/fleet	Year	Fishing gear	FUI (l/t landed catch)	Reference
Anchoveta (*Engraulis ringens*)	Peru/Austral fleet	2019	PS	35.6	Current study
	Peru/ third party fleet	2019	PS	29.2	Current study
	Peru/ Austral fleet	2021	PS	31.0	Current study
	Peru/third party fleet	2021	PS	20.3	Current study
	Peru/< 10 m^3	2008–2010	PS	17.3	Avadí et al. (2014)
	Peru *Vikingas* 50–100 m^3	2008–2010	PS	14.9	Avadí et al. (2014)
	Peru/100–110 m^3	2008–2010	PS	11.9	Avadí et al. (2014)
	Peru/155–235 m^3	2008–2010	PS	17.2	Avadí et al. (2014)
	Peru/235–315 m^3	2008–2010	PS	18.1	Avadí et al. (2014)
	Peru/315–395 m^3	2008–2010	PS	18.4	Avadí et al. (2014)
	Peru/395–475 m^3	2008–2010	PS	18.9	Avadí et al. (2014)
	Peru/ 475–555 m^3	2008–2010	PS	19.5	Avadí et al. (2014)
	Peru/555–635 m^3	2008–2010	PS	17.1	Avadí et al. (2014)
World Average	World Average	2011	–	489	Parker et al. (2018)
DHC	World Average	2011	–	592	Parker et al. (2018)
IHC (not food)	World Average	2011	–	246	Parker et al. (2018)
IHC (fishmeal)	World Average	2011	–	82	Parker et al. (2018)
Pelagic fisheries <30 cm	World Average	2011	–	42	Parker et al. (2018)
Pelagic fisheries >30 cm	World Average	2011	–	430	Parker et al. (2018)
Demersal fish	World Average	2011	–	539	Parker et al. (2018)
Latin America	World Average	2011	–	235	Parker et al. (2018)
Tuna	Ecuador	2012–2013	PS	982	Avadí et al. (2015)
Mackerel (*Scomber scombrus*)	Basque Country (Spain)	2001–2008	PS	32	(Ramos et al., 2011)
Mackerel (*Trachurus trachurus*)	Galicia (Spain)	2008	PS	207	(Vázquez-Rowe et al., 2010)
Mackerel (*Trachurus trachurus*)	Galicia (Spain)	2008	T	584	(Vázquez-Rowe et al., 2010)
Anchovy (*Engraulis encrasicolus*)	Cantabria (Spain)	2015	PS	400	(Laso et al., 2018)
Sardine (*Sardina pilchardus*)	Portugal	2005–2011	PS	108	(Almeida et al., 2014)

DHC = direct human consumption; FUI = fuel use intensity; IHC = indirect human consumption; PS = purse seine; T = trawl.

l/t, significantly lower than the world average for all fisheries (489 l/t) (Table 10). However, the worldwide average FUI for FMFO is substantially higher than that reported for Peru in the present study and in Avadí et al. (2014). In fact, the highest FUI reported for any vessel in our sample was 52 l/t.

Several reasons explain why the Peruvian *E. ringens* fleet features one of the lowest (if not the lowest) industrial fishing FUI throughout the planet. These include distance to fishing grounds, the regional distribution of FMFO production plants along the Peruvian coast, the behavior of the *E. ringens* schools, the regulation and assignment of fishing quotas by the Peruvian Ministry of Production, or the fishing strategy established by the FMFO producing companies, optimizing the fishing effort according to the available stock and remaining quota as the fishing season allowed by the Peruvian authorities' advances (World Bank Group, 2016; Díaz Acuña, 2017). In fact, a study by Bastardie et al. (2022) in Denmark demonstrates that the health of the fishing stock is a determining factor in ensuring that a fishery maintains low FUI levels. Similarly, a study by Ziegler and Hornborg (2014) reached a similar conclusion for the Swedish fishing fleet. The fact that Peruvian authorities have been conducting a precautionary approach to establishing *E. ringens* quotas since early this century, and the lack of significant changes in the reference FUI values reported, are promising datapoints that should be validated in future research. However, it is plausible to assume that the different phases of ENSO are influencing catchability and fishing effort (Bertrand et al., 2020), and, therefore, FUI. Hence, a more detailed historical tracking of the *E. ringens* industrial fishing fleet is needed to identify more reliable trends.

The FUI of third-party vessels was found to be considerably lower than company-owned, consuming between 19 % and 36 % less fuel as compared to company-owned in both years of study. Although their contribution is smaller than company-owned (up to 39 %) the more efficient third-party vessels FUI reduces the overall fuel consumption between 9 % and 13 % as compared to company-owned vessels. This can be explained by the fact that third-party vessels are not bound to company-owned FMFO plants, they are free to choose were to unload their catch, thus reducing travel distance and fuel consumption.

Finally, when the results are analyzed from an endpoint perspective (see Fig. 4), it should be noted that current LCA methods are slightly biased towards terrestrial and freshwater compartments when reporting damages to ecosystem quality. In this sense, certain environmental aspects, such as seabed impact or marine plastic pollution are not quantified in these metrics (Woods et al., 2021). In the specific context of biotic resource depletion, a new impact category related to ecosystem damage has been developed by Hélias et al. (2023) and later updated by Stanford-Clark et al. (2024). This category relates the impacts that the fishing of a specific species in a specific region have on the marine ecosystem quality using a pristine state as reference and in which any removal of fishing stock generates an impact, even if below the maximum sustainable yield limit. In this sense, when considering stock depletion of the *E. ringens* fishery due to the fishing activity and its characterization factor (CF) developed by Stanford-Clark et al. (2024), the impact on ecosystem quality is expected to increase by approximately 16 % overall at an endpoint level. However, it is worth noting that this CF was developed for the whole FAO 87 area, which covers all the west coast of South America (from Colombia to Chile) and for year 2018, not considering the great variability in *E. ringens* due to the ENSO phenomenon (Bertrand et al., 2020) or the specific quota regime of the stock confined to the Peruvian EEZ. Although this is a first effort to estimate the effects of fishing on ecosystem quality and biodiversity, further work must be performed, as these CFs analyze the impact on ecosystem quality from stock depletion based on replenishment capacity, but do not consider the dynamics and relationships between species in the trophic chain; hence, they do not explain how the extraction of a certain species can affect the whole ecosystem. The inclusion of incipient metrics linked to seabed impact (Woods and Verones, 2019) or marine plastics (Corella-Puertas et al., 2023) could further increase the importance of marine-related ecosystem damage impacts.

4.2. FMFO transformation and transport

During FMFO transformation, regardless of the different activities and fuels used, the quality of the *E. ringens* stock is one of the most dominating aspects linked to the environmental performance of Peruvian FMFO production. In 2019, the plant at Ilo reported a fish oil yield of 1.1 %. In contrast, for the same year the remaining plants reported an oil yield ranging between 2.7 % and 4.4 %. This meant that the production of fish oil in Ilo in 2019 presented significantly higher impacts in all categories, as compared to the other plants in both years (see Figure SM11). In contrast, for the same year, fishmeal yield in Ilo remained in a similar range to the weighted average across plants in both years; therefore, its fishmeal production had a similar environmental performance in all impact categories as the other plants, despite having a more carbon-intensive energy mix (see Figure SM10).

The use of antioxidants for fishmeal preservation and, therefore, the derived environmental impacts, vary substantially between plants. For instance, Coishco is the only plant that uses the antioxidant named “Oxilow 20” (see Table SM3), which has a high content of sunflower oil, increasing the impacts considerably for certain categories. In fact, the impact contribution of the antioxidants used in Coishco ranged from 67 % to 73 % for freshwater ecotoxicity; 85 % to 91 % for marine eutrophication; and ca. 90 % in land use. In contrast, the impacts of the antioxidants used in the other plants ranged between 1 % and 8 % of total impacts in the transformation stage for freshwater ecotoxicity, marine eutrophication and land use.

Packaging in the transport stage can contribute considerably to plastic waste, as the fishmeal bags that are discarded prior to embarking tends to be mismanaged in many areas of coastal Peru (Ita-Nagy et al., 2022), producing marine plastic pollution. Overall, approximately 445 g of plastic from fishmeal bags (mainly polypropylene) per t of fishmeal are expected to be discarded when embarking bulk carriers. Moreover, according to the Plastic Footprint Network, Peru has an approximate plastic leakage to the ocean from mismanaged waste of 7.6 % (Plastic Footprint Network, 2024) meaning that approximately 33.8 g of plastic per t of fishmeal produced are released to the ocean, amounting up to over 4 t of plastic yearly.

The use of bulk carriers to transport fishmeal has proven to be the most efficient form of maritime transport. In the case of fishmeal, if 100 % of the company’s production is transported using bulk carriers, all the impact categories will present a reduction ranging from 2 % (marine eutrophication) to 25 % (ozone formation). Furthermore, in terms of GHG emissions, a reduction of 12 % is estimated. In contrast, there is no significant difference when using 100 % bulk carriers for fish oil when considering an energy allocation. Nonetheless, if mass allocation is considered, fish oil transport will have a greater importance (i.e., 13 % for GHG emissions and 18 % for particulate matter formation) and thus, a change to bulk carriers can have a reduction of up to 3 % in GHG emissions. However, it should be noted that the company did not provide a disaggregated distinction between fish oil for DHC and IHC in terms of terrestrial and marine transportation to the final destinations. Hence, for modeling purposes they were treated as one single oil product in the transportation phase.

4.3. Comparison with other marine ingredients and aquaculture feed products

Original research on the environmental impacts of FMFO is scarce in the scientific literature (Newton et al., 2023). However, there are studies available in the literature that can be used as benchmark, although it must be noted that allocation is a determining parameter in the presentation and final interpretation of results.

Fréon et al. (2017) were the first to study the production of FMFO from Peruvian *E. ringens* with an LCA approach considering an energy allocation. Comparing to the results obtained in this study, it can be appreciated that FMFO transformation has presented a considerable reduction in most of the impact categories (see Tables SM27-SM28 in the SM). In 2019 and 2021 the energy efficiency per t of landed *E. ringens* remained nearly constant (1547 and 1543 MJ/t, respectively), showing a 3 % increase compared to results previously reported (Fréon et al., 2017). However, for fishmeal during the transformation process, it showed a reduction of approximately 27 % as compared to a plant using only natural gas and over 45 % as when comparing to a plant using only heavy fuel oil for heat production reported by Fréon et al. (2017). In contrast, 1 t of fish oil emitted 2 % less GHG as compared to a plant using only natural gas and presented a decrease of 29 % compared to a plant using only heavy fuel oil (Fréon et al., 2017). However, important increases are shown in stratospheric ozone depletion due to the electric diesel generators; terrestrial and freshwater ecotoxicity, primarily due to the electricity from the grid and the diesel used for heat production, and at a lesser extent, due to phosphoric acid used as a landed catch preserver; land use, due to the antioxidant added to the fishmeal prior packaging; and water consumption (electricity) because of the high contribution of hydro power in the Peruvian energy mix. Nonetheless, it is worth recognizing that Fréon et al. (2017) used the ReCiPe 2008 as an analysis method, while this study used its 2016 updated version, which not only added extra damage pathways, but also improved the overall impact calculations. Moreover, this study has generated a more comprehensive LCI, considering the use of different types of fossil fuels during the process, as well as nearly all the chemical inputs and their freighting.

In terms of GHG emissions, a study by Cashion et al. (2017) processed information on the main sources of FMFO worldwide according to three main criteria: a) an average annual landed catch of 100,000 t of species intended for FMFO production in the period 2008–2012; b) the species analyzed are usually used for FMFO production; and c) adequate information about the species under study was available, such as trophic level, yields to produce FMFO, fishing gear, FUI, among others. Using an energy allocation, it was found that the GHG emissions of the production of 1 t of fishmeal in the current study (316 to 328 kg CO_2eq on average) are significantly lower than the reported by Cashion et al. (2017), which ranged from 478 to 5570 kg CO_2eq. In contrast, for the case of fish oil, our results indicate that GHG emissions to produce 1 t of fish oil in our study range from 4250 to 4550 kg CO_2eq on average, while a range between 770 and 11,900 kg CO_2eq in Cashion et al. (2017), with most oils varying between 1100 and 2600 kg CO_2eq.

Newton et al. (2023) analyzed the impacts of different FMFO products from different species worldwide, considered an economic allocation (USD 1422 for fishmeal and USD 1501 for fish oil), and mainly used Fréon et al. (2017), Cashion et al. (2017) and other studies data to develop their LCIA. In contrast, the economic allocation used in our study considered USD 1461 for fishmeal and USD 2316 for fish oil. However, these economic allocation results must be interpreted with caution. On the one hand, the economic allocation for fisheries considered by Newton et al. (2023) is based on prices retrieved from OECD/-FAO (2018) 10-year averages. On the other hand, FMFO prices, especially for fish oil, are expected to rise in upcoming years. Therefore, comparisons tend to be distorted based on fluctuating prices in the market. Considering these limitations, the results suggest that Peruvian FMFO is one of the lowest GHG emitters among feed ingredients, and that FMFO production reported in the current study is among the lowest when compared to other whole fishmeal and fish oils. This tendency is also observed for other impact categories, such as terrestrial acidification and freshwater eutrophication.

When considering transport to the port of destination in Europe, Silva et al. (2018) also found that FMFO from Peruvian *E. ringens* had the lowest impacts when comparing it with different feed ingredients. Furthermore, the results obtained in our study show that FMFO products had the lowest environmental impacts in nearly all categories (except terrestrial ecotoxicity), not only when compared to Peruvian fishmeal in the study, but also when compared to Portuguese FMFO from fish by-products, Brazilian soybean meal and oil, and Portuguese poultry meal and fat from by-products (Silva et al., 2018). Fig. 6 illustrates the difference of GHG emissions across the cited literature.

5. Conclusions

The current study constitutes the most recent LCA on FMFO production in Peru, the main producer worldwide. Moreover, we provide updated assessment methods, as well as improved and more detailed datasets in line with methodological, data quality and availability improvements. Given the scarce scientific literature available, we reckon our study will be highly informative for future environmental assessments of aquaculture systems and aquafeeds, as well as other market products that use FMFO.

Peruvian *E. ringens* fishery has proven to be one of the most efficient in the world in terms of fuel use and fishing effort. The vast stock in the region and the establishment of fishing quotas by the Peruvian government have created a fishery that consumed in 2019 and 2021 between 60 % to 67 % less fuel per tonne of landed catch as compared to the average FUI of worldwide reduction fisheries. In this sense, available fish stock is considered an important carrier influencing the environmental profile of this system. For instance, the fishing quota (and therefore landed catch) of 2021 was 61 % higher than in 2019, leading to a 17 % reduction of the FUI, and fuel combustion has proven to be the single-most polluting activity during fishing activities.

Although it seems that the FUI of the *E. ringens* fishery is fairly constant through years without extreme weather events (e.g., moderate to extreme *El Niño* events), future research is needed to continue to evaluate the impacts that the *E. ringens* stock has on FMFO production sustainability in Peru as changes in FUI can dramatically affect its environmental performance. Moreover, warmer waters due to climate change and more frequent *El Niño* events may negatively affect the availability of the stock, resulting in greater fuel consumption and lowering yield.

Fuel use, both during fishing and during transformation, is the most dominant activity in terms of environmental impacts. Moreover, the energy mix used during transformation has proven to be important to

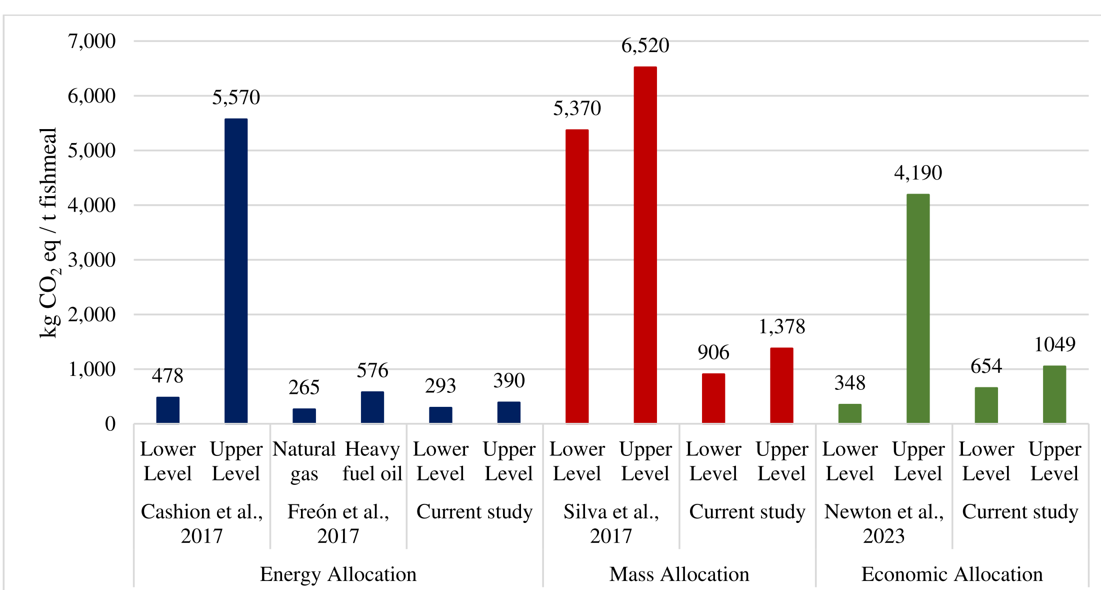

Fig. 6. Fishmeal production greenhouse gas (GHG) emissions comparison between the current study and the available scientific literature, according the allocation considered. Lower and upper levels refer to the minimun and maximum greenhouse gas (GHG) emissions obtained in each study, respectively.

overall impacts. In fact, during transformation, a significant reduction in GHG emissions and most impact categories was observed compared to previous studies, which is mainly due to a change in the fuel mix (while maintaining a similar energy efficiency), by prioritizing natural gas use over diesel and residual fuel oils. Similarly, fish quality (e.g., fat and protein content) is relevant in terms of the environmental performance of FMFO production, as proven for the plant in Ilo in 2019, where a lower fish oil yield compared to 2021, due to a low-fat content in the *E. ringens*, produced significantly higher impacts per t of fish oil produced.

In terms of biodiversity impacts, novel CFs on biotic stock depletion increase the endpoint ecosystem quality damage results. However, these CFs do not integrate ecosystem dynamics and the temporal change in stocks due to climate conditions. In parallel, the impacts on marine ecosystems related to plastic pollution generated in FMFO production are not fully represented in this study, which could also increase the final damage impacts. Hence, although several marine-related impact pathways and, therefore, CFs, are currently lacking or not fully available in LCA, it is expected that these would contribute notably to ecosystem qualiy impacts.

From a methodological perspective, the allocation method is of great importance when analyzing FMFO products when communicating LCA results. For instance, when considering biophysical dimensions, Peruvian anchoveta FMFO production is one of the lowest impact options among marine ingredients for aquafeed. However, when analyzing Peruvian FMFO environmental impact results from an economic perspective, this interpretation is less evident, as its values, while still low compared to other aquafeeds, rank higher than when energy or mass allocation are applied. Moreover, when compared to terrestrial-based feed ingredients with a mass allocation, Peruvian FMFO was found to have one of the best environmental performances. Thus, allocation preferences of marine ingredients for aquafeed LCA studies should be transparent and standardized to avoid misinterpretations and greenwashing.

Finally, we emphasize the importance of this fishery in different sectors, especially in the oil industry. Peru as a leading fishing and FMFO producing country also has one of the lowest environmental footprints, namely carbon, of feed ingredients. With fish oil prices rising, and an ever-growing demand for farmed fish and animal feed, if managed accordingly, the Peruvian *E. ringens* fishery will become a major player for achieving a sustainable exploitation of our oceans.

CRediT authorship contribution statement

Alejandro Deville: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ian Vázquez-Rowe:** Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Angel Avadí:** Writing – review & editing, Visualization, Resources, Conceptualization. **Fernando Miranda:** Writing – review & editing, Visualization, Conceptualization. **Ramzy Kahhat:** Writing – review & editing, Visualization, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests:

The study has been partially funded by Austral S.A.A., an important marine ingredients company in Peru. However, the authors declare that neither these nor any other interests have directly or indirectly influenced the objectivity of this paper, and the findings and conclusions in the paper are those of the authors alone, independent of their organizations or funding sources.

Acknowledgements

The authors thank the Natural Environment Research Council (NERC) of the United Kingdom for financial support via the “Reducing the impacts of plastic waste in the Eastern Pacific Ocean” project (NERC reference: NE/V005448/1). Alejandro Deville, Ian Vázquez-Rowe and Ramzy Kahhat thank the European Union’s Horizon Europe research and innovation programme for funding the BAMBOO Project (101059379). The Austral Group S.A.A. of the Austevoll Seafood Company and Oscar Sunción are acknowledged for their invaluable contributions.

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Research Executive Agency (REA), the Swiss Confederation, or the Swiss State Secretariat for Education, Research and Innovation (SERI). Neither the European Union, the Swiss Confederation, nor the granting authorities can be held responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2025.742239.

Data availability

Data will be made available on request.

References

Avadí, A., Vázquez-Rowe, I., Fréon, P., 2014. Eco-efficiency assessment of the Peruvian anchoveta steel and wooden fleets using the LCA+DEA framework. J. Clean. Prod. 70, 118–131.
Almeida, C., Vaz, S., Cabral, H., Ziegler, F., 2014. Environmental assessment of sardine (Sardina pilchardus) purse seine fishery in Portugal with LCA methodology including biological impact categories. The International Journal of Life Cycle Assessment 19, 297–306.
Avadí, A., Acosta-Alba, I., 2021. Eco-efficiency of the fisheries value chains in the gambia and mali. Foods 10 (7), 1620.
Avadí, A., Pelletier, N., Aubin, J., Ralite, S., Núñez, J., Fréon, P., 2015. Comparative environmental performance of artisanal and commercial feed use in Peruvian freshwater aquaculture. Aquaculture 435, 52–66.
Avadí, A., Vázquez-Rowe, I., Symeonidis, A., Moreno-Ruiz, E., 2020. First series of seafood datasets in ecoinvent: setting the pace for future development. Int. J. Life Cycle Assess. 25, 1333–1342.
Banco Central de Reserva, 2023a. Estadísticas: precio harina de pescado. https://estadisticas.bcrp.gob.pe/estadisticas/series/anuales/resultados/PM05419BA/html [in Spanish]. Last accessed: May 12 2024.
Banco Central de Reserva, 2023b. Estadísticas: precio aceite de pescado. https://estadisticas.bcrp.gob.pe/estadisticas/series/anuales/resultados/PM05422BA/html [in Spanish]. Last accessed: June 8th 2023.
Bastardie, F., Hornborg, S., Ziegler, F., Gislason, H., Eigaard, O.R., 2022. Reducing the fuel use intensity of fisheries: through efficient fishing techniques and recovered fish stocks. Frontiers in Marine Science 9, 817335.
Bertrand, S., Dewitte, B., Tam, J., Díaz, E., Bertrand, A., 2008. Impacts of Kelvin wave forcing in the Peru Humboldt Current system: Scenarios of spatial reorganizations from physics to fishers. Prog. Oceanogr. 79 (2–4), 278–289.
Bertrand, A., Lengaigne, M., Takahashi, K., Avadi, A., Poulain, F., Harrod, C., 2020. El Niño Southern Oscillation (ENSO) effects on fisheries and aquaculture, Vol. 660. Food & Agriculture Org.
Bohnes, F.A., Laurent, A., 2019. LCA of aquaculture systems: methodological issues and potential improvements. Int. J. Life Cycle Assess. 24, 324–337.
CAN, 2015. Parque vehicular en la Comunidad Andina (2005–2014). http://intranet.comunidadandina.org/Documentos/DEstadisticos/SGde707.pdf.
Cashion, T., Le Manach, F., Zeller, D., Pauly, D., 2017. Most fish destined for fishmeal production are food-grade fish. Fish Fish. 18 (5), 837–844.
Chávez, F., Bertrand, A., Guevara-Carrasco, R., Soler, P., Csirke, J., 2008. The northern Humboldt Current System: brief history, present status and a view towards the future. (Editorial). Progress in Oceanography 79, 95–105.
Ciroth, A., Muller, S., Weidema, B., Lesage, P., 2016. Empirically based uncertainty factors for the pedigree matrix in ecoinvent. Int. J. Life Cycle Assess. 21, 1338–1348.
Coelho, C.R., Peters, G., Zhang, J., Abdollahi, M., Undeland, I., 2023. Fish beyond fillets: Life cycle assessment of cross-processing herring and lingonberry co-products into a food product. Resour. Conserv. Recycl. 188, 106703.
Corella-Puertas, E., Hajjar, C., Lavoie, J., Boulay, A.M., 2023. MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments. J. Clean. Prod. 418, 138197.

Deville, A., Vazquez-Rowe, I., Ita-Nagy, D., Kahhat, R., 2023. Ocean-based sources of plastic pollution: An overview of the main marine activities in the Peruvian EEZ. Mar. Pollut. Bull. 189, 114785.
Díaz Acuña, E., 2017. Impacto de diferentes estrategias de explotación sobre el estado inmediato del stock norte-centro de la anchoveta peruana (*Engraulis ringens*). Master Thesis at the Universidad Nacional Mayor de San Marcos. Retrieved from: https://repositorio.imarpe.gob.pe/bitstream/20.500.12958/3171/1/Diaz%20Acu%c3%b1a%20E.pdf [in Spanish].
Ecoinvent, 2024a. System models. Retrieved from: https://support.ecoinvent.org/system-models#Allocation_Substitution. Latest accessed: April 15th 2024.
Ecoinvent, 2024b. Data with purpose. Retrieved from: https://ecoinvent.org/. Latest accessed: October 8th 2024.
European Environment Agency, 2017. Life cycle assessment. https://www.eea.europa.eu/help/glossary/eea-glossary/life-cycle-assessment#:~:text=Life%2Dcycle%20assessment%20(LCA),use%20efficiency%20and%20decreasing%20liabilities. Latest accessed: October 15th 2024.
FAO, 2024. The State of World Fisheries and Aquaculture 2024 – *Blue Transformation in action.* Rome. https://doi.org/10.4060/cd0683en.
Fiorella, K.J., Okronipa, H., Baker, K., Heilpern, S., 2021. Contemporary aquaculture: implications for human nutrition. Curr. Opin. Biotechnol. 70, 83–90.
Fréon, P., Avadí, A., Vinatea Chavez, R.A., Iriarte Ahón, F., 2014. Life cycle assessment of the Peruvian industrial anchoveta fleet: Boundary setting in life cycle inventory analyses of complex and plural means of production. Int. J. Life Cycle Assess. 19 (5), 1068–1086.
Fréon, P., Durand, H., Avadí, A., Huaranca, S., Orozco Moreyra, R., 2017. Life cycle assessment of three Peruvian fishmeal plants: Toward a cleaner production. J. Clean. Prod. 145, 50–63.
Gephart, J.A., Henriksson, P.J., Parker, R.W., Shepon, A., Gorospe, K.D., Bergman, K., Troell, M., et al., 2021. Environmental performance of blue foods. Nature 597 (7876), 360–365.
Glencross, B., Ling, X., Gatlin, D., Kaushik, S., Øverland, M., Newton, R., Valente, L.M., 2024. A SWOT Analysis of the Use of Marine, Grain, Terrestrial-Animal and Novel Protein Ingredients in Aquaculture Feeds. Rev. Fisheries Sci. Aquacult. 1–39.
Hélias, A., Stanford-Clark, C., Bach, V., 2023. A new impact pathway towards ecosystem quality in life cycle assessment: characterisation factors for fisheries. Int. J. Life Cycle Assess. 28 (4), 367–379.
Horsnell, C., 2018. From Fish to Fish – Evaluating the SocioEnvironmental Consequences of the Vietnamese Fishmeal Industry. A Life Cycle Assessment and Product Chain Organisation Analysis of the Production of Vietnamese Fishmeal. Master Thesis dissertation at Chalmers. University of Technology.
Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., Van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147.
IFFO, 2009. International Fishmeal and Fish Oil Organisation 50th anniversary.
ISO, 2006. ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework. International Standards Organization, Geneva, Switzerland.
Ita-Nagy, D., Vázquez-Rowe, I., Kahhat, R., 2022. Developing a methodology to quantify mismanaged plastic waste entering the ocean in coastal countries. J. Ind. Ecol. 26 (6), 2108–2122.
Jannathulla, R., Rajaram, V., Kalanjiam, R., Ambasankar, K., Muralidhar, M., Dayal, J.S., 2019. Fishmeal availability in the scenarios of climate change: Inevitability of fishmeal replacement in aquafeeds and approaches for the utilization of plant protein sources. Aquac. Res. 50 (12), 3493–3506.
Jara, H.J., Tam, J., Reguero, B.G., Ganoza, F., Castillo, G., Romero, C.Y., Sánchez, A.A., 2020. Current and future socio-ecological vulnerability and adaptation of artisanal fisheries communities in Peru, the case of the Huaura province. Mar. Policy 119, 104003.
Jonell, M., Henriksson, P.J.G., 2015. Mangrove–shrimp farms in Vietnam—Comparing organic and conventional systems using life cycle assessment. Aquaculture 447, 66–75.
Kok, B., Malcorps, W., Tlusty, M.F., Eltholth, M.M., Auchterlonie, N.A., Little, D.C., Harmsen, R., Newton, R.W., Davies, S.J., 2020. Fish as feed: Using economic allocation to quantify the Fish In: Fish Out ratio of major fed aquaculture species. Aquaculture 528, 735474.
Kosseva, M.R., 2020. Sources, characteristics, treatment, and analyses of animal-based food wastes. In: Food Industry Wastes. Academic Press, pp. 67–85.
Laso, J., Vázquez-Rowe, I., Margallo, M., Crujeiras, R.M., Irabien, Á., Aldaco, R., 2018. Life cycle assessment of European anchovy (Engraulis encrasicolus) landed by purse seine vessels in northern Spain. The International Journal of Life Cycle Assessment 23, 1107–1125.
MacLeod, M.J., Hasan, M.R., Robb, D.H.F., Mamun-Ur-Rashid, M., 2020. Quantifying greenhouse gas emissions from global aquaculture. Sci. Rep. 10 (1), 1–8.
Mahamud, A.S.U., Anu, M.S., Baroi, A., Datta, A., Khan, M.S.U., Rahman, M., Rahman, T., 2022. Microplastics in fishmeal: A threatening issue for sustainable aquaculture and human health. Aquacult. Reports 25, 101205.
MINAM, 2020. Reporte Anual de Gases de Efecto Invernadero del sector Energía del año 2016 Categorías: Combustión Estacionaria y Emisiones Fugitivas. Ministerio del Ambiente, Lima, Perú.
MINAM, 2021. Inventario Nacional de Gases de Efecto Invernadero (INGEI).
Moron, G., Galloso, P., Gutierrez, D., Torrejon-Magallanes, J., 2019. Temporal changes in mesoscale aggregations and spatial distribution scenarios of the Peruvian anchovy (*Engraulis ringens*). Deep-Sea Res. II Top. Stud. Oceanogr. 159, 75–83.
Newton, R.W., Maiolo, S., Malcorps, W., Little, D.C., 2023. Life cycle inventories of marine ingredients. Aquaculture 565, 739096.
OECD/FAO, 2018. OECD-FAO Agricultural Outlook 2018–2027. OECD Publishing, Paris/FAO, Rome. https://doi.org/10.1787/agr_outlook-2018-en.
Paredes, C.E., 2023. Dualidad y alineamiento de incentivos en la pesca. Diario Gestión. Available at: https://gestion.pe/opinion/dualidad-y-alineamiento-de-incentivos-en-la-pesca-opinion-peru-estado-pesca-imarpe-recursos-hidrobiologicos-noticia/ [in Spanish]. Last accessed: June 8th 2023.
Parker, R.W.R., Blanchard, J.L., Gardner, C., Green, B.S., Hartmann, K., Tyedmers, P.H., Watson, R.A., 2018. Fuel use and greenhouse gas emissions of world fisheries. Nat. Clim. Chang. 8 (4), 333–337.
Pelletier, N., Tyedmers, P., 2011. An ecological economic critique of the use of market information in life cycle assessment research. J. Ind. Ecol. 15 (3), 342–354.
Pelletier, N., Ardente, F., Brandão, M., De Camillis, C., Pennington, D., 2015. Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? Int. J. Life Cycle Assess. 20, 74–86.
Péron, G., Mittaine, J.F., Le Gallic, B., 2010. Where do fishmeal and fish oil products come from? An analysis of the conversion ratios in the global fishmeal industry. Mar. Policy 34 (4), 815–820.
Plastic Footprint Network – PFN, 2024. Harmonized methodology for assessing plastic leakage and impact. Available at: https://www.plasticfootprint.earth/assessment-methodology/. Last accessed: October 12th 2024.
Pörtner, H.O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Ibrahim, Z.Z., 2022. Climate change 2022: Impacts, adaptation and vulnerability. IPCC, Geneva, Switzerland, p. 3056.
Ramos, S., Vázquez-Rowe, I., Artetxe, I., Moreira, M.T., Feijoo, G., Zufía, J., 2011. Environmental assessment of the Atlantic mackerel (Scomber scombrus) season in the Basque Country. Increasing the timeline delimitation in fishery LCA studies. The International Journal of Life Cycle Assessment 16, 599–610.
Richardson, K., Hardesty, B.D., Wilcox, C., 2019. Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. Fish Fish. 20 (6), 1218–1231.
Ruiz-Salmón, I., Laso, J., Margallo, M., Villanueva-Rey, P., Rodríguez, E., Quinteiro, P., Aldaco, R., et al., 2021. Life cycle assessment of fish and seafood processed products–a review of methodologies and new challenges. Sci. Total Environ. 761, 144094.
Sánchez-Durand, N., Gallo-Seminario, M., 2009. Status of and trends in the use of small pelagic fish species for reduction fisheries and for human consumption in Peru. Fish as feed inputs for aquaculture, p. 325.
Shepherd, C.J., Jackson, A.J., 2013. Global fishmeal and fish-oil supply: inputs, outputs and markets. J. Fish Biol. 83 (4), 1046–1066.
Silva, C.B., Valente, L.M., Matos, E., Brandão, M., Neto, B., 2018. Life cycle assessment of aquafeed ingredients. Int. J. Life Cycle Assess. 23, 995–1017.
Stanford-Clark, C., Loiseau, E., Helias, A., 2024. Fisheries impact pathway: making global and regionalised impacts on marine ecosystem quality accessible in life cycle impact assessment. Sustainability 16 (9), 3870.
Swanson, D., Block, R., Mousa, S.A., 2012. Omega-3 fatty acids EPA and DHA: health benefits throughout life. Adv. Nutr. 3 (1), 1–7.
Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2010. Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain): comparative analysis of two major fishing methods. Fisheries Research 106 (3), 517–527.
Vázquez-Rowe, I., Reyna, J.L., García-Torres, S., Kahhat, R., 2015. Is climate change-centrism an optimal policy making strategy to set national electricity mixes? Applied energy 159, 108–116.
Wang, Q., Li, J., Zhu, X., Sun, C., Teng, J., Chen, L., Zhao, J., et al., 2022. Microplastics in fish meals: An exposure route for aquaculture animals. Sci. Total Environ. 807, 151049.
Weidema, B.P., Schmidt, J.H., 2010. Avoiding Allocation in Life Cycle Assessment Revisited. J. Ind. Ecol. 14 (2).
Wintersteen, K.A., 2021. The fishmeal revolution: The industrialization of the Humboldt current ecosystem. Univ of California Press.
Woods, J.S., Verones, F., 2019. Ecosystem damage from anthropogenic seabed disturbance: a life cycle impact assessment characterisation model. Sci. Total Environ. 649, 1481–1490.
Woods, J.S., Verones, F., Jolliet, O., Vázquez-Rowe, I., Boulay, A.M., 2021. A framework for the assessment of marine litter impacts in life cycle impact assessment. Ecol. Indic. 129, 107918.
World Bank Group, 2016. Peru - First, Second, and Third Environmental Development Policy Loans Project Peru. In: First, Second, and Third Environmental Development Policy Loan Projects (English). Washington, D.C.
Ziegler, F., Hornborg, S., 2014. Stock size matters more than vessel size: the fuel efficiency of Swedish demersal trawl fisheries 2002–2010. Mar. Policy 44, 72–81.
Ziegler, F., Hornborg, S., Green, B.S., Eigaard, O.R., Farmery, A.K., Hammar, L., Hartmann, K., Molander, S., Parker, R.W.R., Skontorp Hognes, E., Vázquez-Rowe, I., Smith, A.D.M., 2016. Expanding the concept of sustainable seafood using Life Cycle Assessment. Fish Fish. 17 (4), 1073–1093.