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Environmental performance of Cantabrian (Northern Spain) pelagic fisheries: Assessment of purse seine and minor art fleets under a life cycle approach

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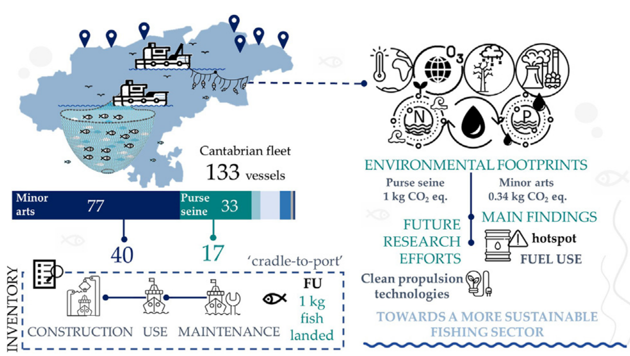
HIGHLIGHTS

- LCA is an effective tool for the environmental assessment of fisheries.
- Vessel fuel use represents the main carrier of detrimental environmental impacts.
- FUI reduction has the greatest potential to lower CC and most impact indicators.
- Purse seiners perform worse than minor art vessels.

GRAPHICAL ABSTRACT



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ABSTRACT

The perpetuation of fishing activity from an environmentally, socially and economically sustainable approach is essential to guarantee not only the future of coastal populations, but also the supply of high-value seafood for society and the safeguarding of cultural heritage.

This article aims to assess the environmental performance associated with fishing fleet operations in Cantabria (northern Spain) under a life cycle thinking from a holistic approach. Thus, the Life Cycle Assessment (LCA) methodology was applied under a 'cradle-to-port' approach, setting the functional unit as 1 kg of fresh fish landed. Inventory data on the main inputs and outputs were collected from a sample of 57 vessels covering for the first time the main techniques, purse seine and minor art fisheries.

The results identified that the vessel use stage was the responsible of most of the impacts. In line with the literature, diesel consumption stood as the chief hotspot in six of the seven impact categories analysed. Purse seiners got a value of 0.25 kg of fuel per kg of fish landed, while the performance of the minor art fleet showed significantly lower consumption (0.07). Regarding impacts on climate change, this study found a quantity of 1.00 and 0.34 kg CO_2 eq. per FU, for purse seine and minor arts, respectively. These figures were consistent with the expected results for pelagic fisheries. For the remaining indicators, purse seiners generally performed worse.

The LCA methodology provided outcomes that allow the proposal of potential improvements and measures to foster the transition towards a more sustainable smart-fishing sector. Further research efforts should focus on the development and implementation of renewable energy and low-carbon vessel propulsion technologies.

1. Introduction

Within the wide range of human activities linked to oceans and seas, fisheries stand out as a fundamental guarantor of food security worldwide and play a key role in structuring coastal communities, where employment

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and economic activity are closely linked to their sustainability and prosperity (MAPA, 2022a).

Over the past few years, the global fisheries sector has suffered the severe consequences of the COVID-19 pandemic (FAO, 2020a; Ruiz-Salmón et al., 2021a) and is being hit directly from the impact of the energy price crisis due to the fact that the price of fuel is a critical element for the fishing activity (Fernández-Ríos et al., 2022). In fact, the European fleet consumes about 2 million l of fuel, which can represent up to 40 % of total costs in some segments (STECF, 2020). In fact, some fleets such as the Spanish, announced in March 2022 their intention to stop their activity due to the sharp increase in the price of diesel (MAPA, 2022b). Despite these difficulties, the fishing sector is clear example of resilience, demonstrating its commitment and responsibility to ensure the supply of this commodity (CEPESCA, 2020). It represents a broad, fast-moving segment of the economy, which over the past decade has taken significant steps to modernise and diversify (European Commission, 2021).

Fish and seafood play an essential role in healthy and balanced diets, as they are an important source of protein (Laso et al., 2018a). This is especially true for the average person living in the EU, who consumes 24.4 kg of fish or seafood per year, 4 kg more than in the rest of the world (EUMOFA, 2021). According to the latest FAO estimates, fish accounted for about 17 % of total animal protein and 7 % of all protein consumed globally in 2017 (FAO, 2020b). Furthermore, research suggests that the nutritional benefit of fish goes beyond this, since it is a valuable source of fatty acids, including the omega-3 polyunsaturated fatty acids (n-3 FAs), micronutrients (P, I, Zn, Fe, and Se) and vitamins (D, A, and B) with variations among species (Qayoom et al., 2020).

The EU is the world's fifth largest producer, with about 3.3 % of total fisheries and aquaculture production, with fisheries accounting for 80 % of total fish production (FAO, 2020b). By country, Spain, Denmark, the UK and France are the main producers in volume terms within the EU (European Commission, 2020a).

Focusing in Spain, the fishing sector constitutes a notable element of the national economy as well. Indeed, the Spanish fleet is considered by some bodies to be the largest in the European Union (MAPA, 2022a). By the end of 2021, Spain had 8732 vessels in force, with 88 % of the total in active conditions. The Spanish fleet operating in the waters of the national fishing grounds represents almost 96 %, and approximately 36 % of the tonnage and 62 % of the total kW, with an average age and length of 35 years and 12 m respectively (Secretaría General de Pesca, 2021). The most important national fishing ground in terms of number of vessels, tonnage and power is the one located in the Cantabrian and Northwest (CNW) area, corresponding with the FAO fishing zone 27, subarea VIII —Bay of Biscay (European Commission, 2022a) (Fig. 1), with more than half of the Spanish vessels (4584), a tonnage of 53,385 GT and a power of 203,405 kW. The majority of the fleet is made up of minor art vessels (90.5 %) and around 88 % are located in Galicia, with the remaining 12 % distributed between Asturias, the Basque Country and Cantabria (FAO, 2020b).

Despite not being the autonomous community with the highest fishing figures, the maritime sector in Cantabria (Fig. 1) has a total impact of 11 % of GDP and accounts for 10 % of regional employment (ICANE, 2021). The landed catches reached 25,000 t of auctioned fishing in 2019, valued at 47.6 million euros (ICANE, 2021). Likewise, the marine-related industry continues to promote and grow in the field of R&D&I, digitalisation and new technologies, representing 23 % and 8 % of industrial and total regional R&D&I expenditure, respectively (Clúster MARCA, 2021). The 133 Cantabrian vessels, distributed among 7 ports, are mainly engaged in minor arts (77) and purse seine fishing (33) (Dirección General de Pesca y Alimentación, 2022). The rest of the vessels are divided between bottom trawling, longlining, dredging and gillnetting. According to the records of the different fishermen's associations in the region (OPECA), the main species caught include European anchovy (*Engraulis encrasicolus*), tuna species (mainly *Thunnus alalunga*), European pilchard (*Sardina pilchardus*), Atlantic mackerel (*Scomber scombrus*) and Atlantic horse mackerel (*Trachurus trachurus*).

The perpetuation of fishing activity from an environmentally, socially and economically sustainable approach is essential to ensure not only the future of these populations and their proper structuring but also the

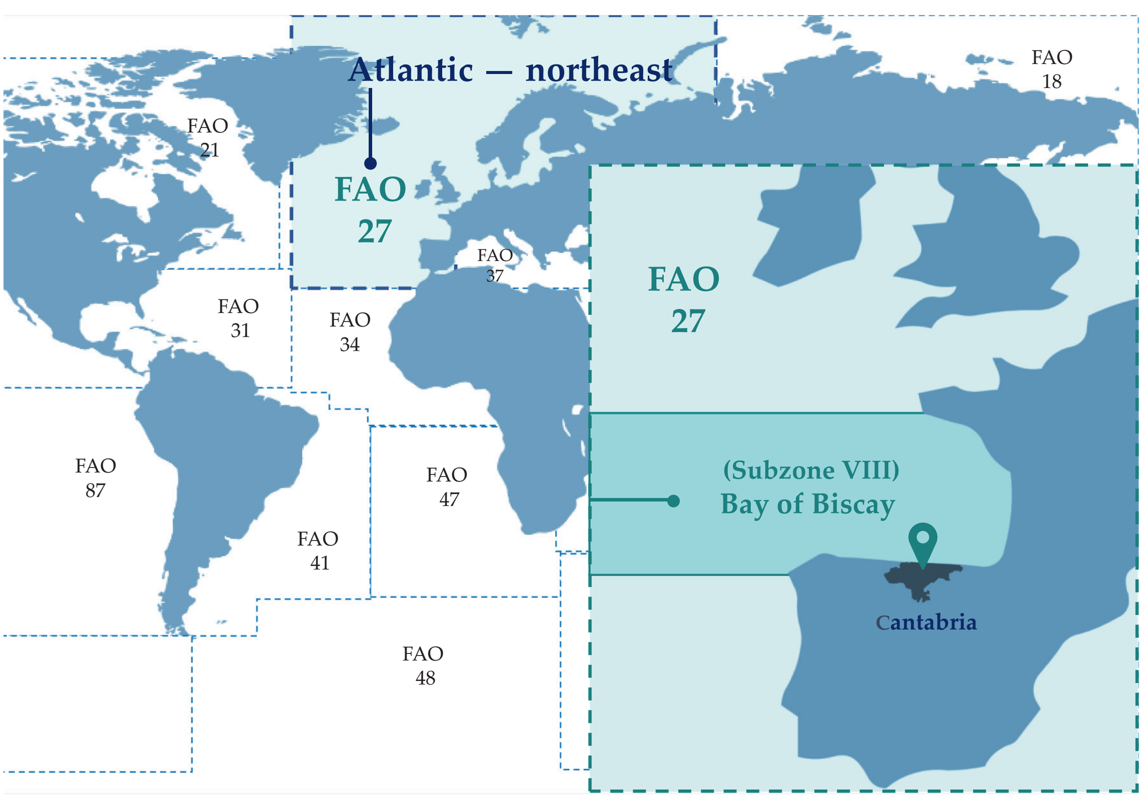


Fig. 1. Geographical boundaries of the International Council for the Exploration of the Sea (ICES), highlighting FAO area 27 and subdivision 8 corresponding to the Bay of Biscay.

provision of seafood to society in a sustainable way and the safeguarding of cultural heritage (Khakzad and Griffith, 2016). The protection of marine biodiversity is an unavoidable duty in any society as set out in the United Nations 2030 Agenda for Sustainable Development (Red Española de Pacto Mundial, 2022). The SDG14 claim to 'Conserve and sustainably use the oceans, seas and marine resources for sustainable development', as these water bodies produce half of the oxygen we breath and provide 16 % of the animal protein we eat (European Commission, 2022b). More specifically, SDG14 focuses on the so-called 'Blue Economy', i.e. all activities related to the oceans, seas and coastal environments, including living marine resources, non-living resource extraction, maritime transport, port activities, shipbuilding and repair, and coastal tourism (Naciones Unidas, 2022).

Fishing activities cause cumulative impacts on the vast size marine ecosystems, from visible pollution such as plastic litter, 'ghost' gears and oil spills, to invisible pollution such as microplastics (MPs), underwater noise, chemicals and nutrients (Gilman et al., 2022). The effects of greenhouse gas (GHG) emissions are devastating for the oceans, coasts and people living in these areas (Ruiz-Salmón et al., 2020). They range from changes in water temperature to acidification, sea level rise and more frequent and intense flooding and erosion events (Gaines et al., 2019). In addition, illegal fishing, over-exploitation of resources and depletion of fish stocks also pose major threats that harm livelihoods of coastal communities and lead to important biodiversity losses. The value of catches considered 'Illegal, Unreported and Unregulated (IUU)' has recently been estimated at around €10 billion each year, corresponding to almost 20 % of the value of global catches (European Commission, 2020b). All of these menaces will challenge the resilience of the blue economy and society as a whole, but particularly in developing countries (Mason et al., 2022).

These figures support that the blue economy is central to achieving the objectives of the European Green Deal 'Farm to fork' strategy (European Commission, 2022c) and Circular Economy Action Plan (CEAP) (European Commission, 2022d): the transition to a circular model, and the transformation and digitalisation to become a fairer, more resilient, resource-efficient and competitive economy, phasing out net GHG emissions and protecting the natural capital (Laso et al., 2022).

In this context, the standardised Life Cycle Assessment (LCA) methodology has proven to be the most established scientific tool to quantify the potential environmental burdens of fisheries throughout the whole cycle (Avadí and Fréon, 2013). The current literature offers several publications addressing the comprehensive review of fisheries-related LCA studies such as those by Avadí and Fréon (2013), Avadí et al. (2020), and the most updated by Ruiz-Salmón et al. (2021a). Other LCA revisions carried out by Vázquez-Rowe et al. (2012a) and Ziegler et al. (2016) also delved primarily into the fisheries sector and associated supply chain. On the other hand, there are also a wide number of studies focused on specific species or fishing arts, for instance, analysis of the whole life cycle of European anchovy (Laso et al., 2016; Laso et al., 2017a) and Peruvian anchoveta (Avadí et al., 2014a, 2014b; Fréon et al., 2014a); and purse seine pelagic fisheries in the North Atlantic for horse mackerel (Vázquez-Rowe et al., 2010), sardine (Almeida et al., 2014) and Atlantic mackerel (Ramos et al., 2011). Hence, this study aims to evaluate the environmental impacts of the Cantabrian purse seine and minor art fisheries in order to identify hot spots, by means of the LCA methodology. The novelty of this study is justified by the fact that, although fishing sector has been extensively studied from an environmental point of view with specific case studies for certain regions and species, to the best of our knowledge, the assessment of the Cantabrian fleet from a holistic approach comparing its two mains fishing arts is still not covered.

The outcomes of this work will be helpful for the wholesale and retail fisheries sector to improve their eco-labelling references, thus ensuring more valuable information to the final consumer on their environmental commitment, as well as facilitating the traceability of products, as these requirements are increasingly demanded in fishing practices. Moreover, these remarks can also be useful for decision-makers in the current context of sustainable policies ever more relevant.

2. Materials and methods

The LCA methodology was used following the recommendations provided by the ISO 14040 and 14044 standards (ISO, 2006a, 2006b). This approach enables the analysis of the environmental burdens associated with each stage of the fishing life cycle, from the extraction of resources and the processing of raw materials to vessels and nets construction to the landing of fish at port. According to the standards, an LCA study must include the goal and scope definition, the life cycle inventory (LCI) compilation, the life cycle impact assessment (LCIA) and an iterative interpretation of the results. In addition, the sampling of the fleet complied with the requirements of PAS 2050-2 (BSI, 2012) specific to seafood and other aquatic food products.

2.1. Goal and scope definition

This study aimed to bring forward a thorough quantification of the environmental impacts linked to the fishing activity by the Cantabrian purse seine and minor art fleet. As previously remarked, these fishing practices represent 83 % of the total, so the results of this study will provide a representative picture of all vessels in the region.

Cantabrian purse seines have a total tonnage of 4326 GT and an aggregate engine power of 9425 kW. They usually operate in the open ocean to target dense schools of single-species pelagic (midwater) like tuna and mackerel. A vertical net 'curtain' is used to surround the school of fish, the bottom of which is then drawn together to enclose them (Fig. 2a). This technique is generally considered an efficient form of fishing as it has no contact with the seabed and can have low levels of bycatch (accidental catch of unwanted species). On the other hand, the modality of minor arts (Fig. 2b), also known as artisanal fishing, is usually made up of small-sized boats (total tonnage 754 GT) fishing with little nets close to the coast, and therefore have small power engines (a total of 4149 kW). In general, they combine several fishing modalities, all based on net arts, such as longlines and gillnets. Longline fisheries trail a long line, or main line, behind a boat and baited hooks are attached to the nets at intervals to attract the target species. On the other side, gillnet fishing consists of a wall or curtain of net hanging in the water. The dimension of fish caught can be determined by the mesh size, helping to avoid catching juvenile fish. Without careful management, these two minor art fisheries can have unintended interactions with non-target fish, seabirds, and other marine life.

2.2. Function and functional unit

The overall function of the system was the capture and landing of fresh fish in the different ports of the Cantabrian region by the purse seine and minor art fleets. The selection of a coherent function unit (FU) is a fundamental step in order to perform a robust and comparable LCA. Consequently, the selected FU, i.e. the quantifiable reference to which material and energy input/output flows are linked, was set as 1 kg of landed fresh fish by Cantabrian fleet in year 2019. The selection of a mass-based FU was consistent with previous LCA studies focused on the extraction stage, as reported by Ruiz-Salmón et al. (2021a), and was selected so that results scale to quantities that are familiar from everyday interactions, which helps to interpret and understand the results since it reflected a physical variable. Other common FU used in environmental assessments of foods are energy-based and nutrient-based reference flows, but these seem to be more appropriate for studies that extend into the processing and consumption phase of the product (Mcauliffe et al., 2020).

2.3. System boundaries

The system under study encompasses the stages of the vessel's life cycle that constitute the so-called 'cradle-to-port' approach, i.e. from capture to landing fish: raw materials extraction, construction, use and maintenance. This common focus includes the manufacturing processes of the hull, engine and nets, as well as the consumption of lubricant, diesel fuel, ice,

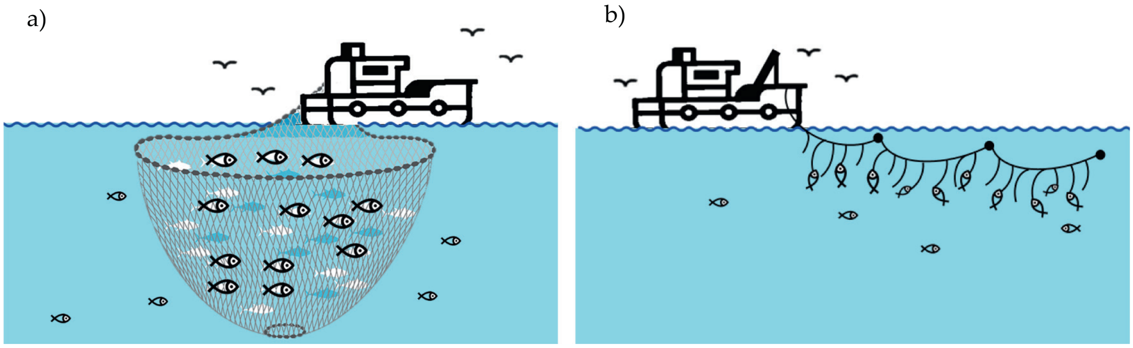


Fig. 2. Simplified graphical representation of the two fishing techniques studied in Cantabria: a) purse seine fishing b) longline (minor arts) fishing.

paint and antifouling, and their related emissions, as shown in Fig. 3. Port landing operations and vessel dismantling were excluded from the system boundary (see Fig. 3), as well as a number of biological issues, such as seafloor use, as their consideration implies impact categories that are not fully developed in the current LCA methodology (Vázquez-Rowe et al., 2012a). Besides, electronic devices, refrigeration systems and crew impact (i.e. emissions on board) were also left out of the analysis.

2.4. Allocation

The Cantabrian fleet under scope operates in a multi-species fishery. Therefore, direct and indirect inputs and outputs from fishing operations, in addition to the resulting environmental burdens, must be allocated among the different target species (Ayer et al., 2007). Even though initially the results of this research will be given by the defined FU, for the subsequent discussion and comparison with other references in the literature, an allocation system will be used. Although different types of allocation procedures could be evaluated in this particular study, e.g. mass, economic, energy; given that the system boundaries were limited to the landing of fish at port, mass allocation was selected as the most appropriate approach (Laso et al., 2017b). The reason is that, following the PEFCR, mass allocation is considered to better reflect reality over longer periods and changing economic conditions, such as those during the pandemic and crisis, apart from not being highly affected by the volatile economic price of the product, which depends on the season, freshness and many other market factors (Laso et al., 2022). In addition, this approach provides a clearer perspective for communicating results to stakeholders at this early stage of the supply chain (Laso et al., 2018b) and facilitates to contrast outcomes with other similar fisheries studies, in which the use of 1 kg of fish as a functional unit is the most established. Allocation percentages were calculated from the data on the total catches of each species recorded by the questionnaires during the collection of inventories in 2019. Tables 1 and 2 below show the main species captured and the mass allocation percentages separating the fleet into purse seiners and minor arts, respectively. Standard deviations were calculated in order to quantify the dispersion of the catch data set, obtaining high values for some species (tuna) fished using minor art techniques. This may be due to variation in vessel size and the use of different numbers of trammel nets and longlines with hooks, individually or in combination. Contrariwise, purse seiners recorded more standardised sizes and characteristics and therefore generally more homogeneous catches.

2.5. Data acquisition and life cycle inventory (LCI)

2.5.1. Primary data

Fishing activity data for the year 2019 were collected from a sample of 17 purse seine and 40 minor art vessels out of a total of 33 and 77 respectively, belonging to the Cantabrian fleet. The sample represented 51–52 % of this fleet, meeting the representativeness requirements

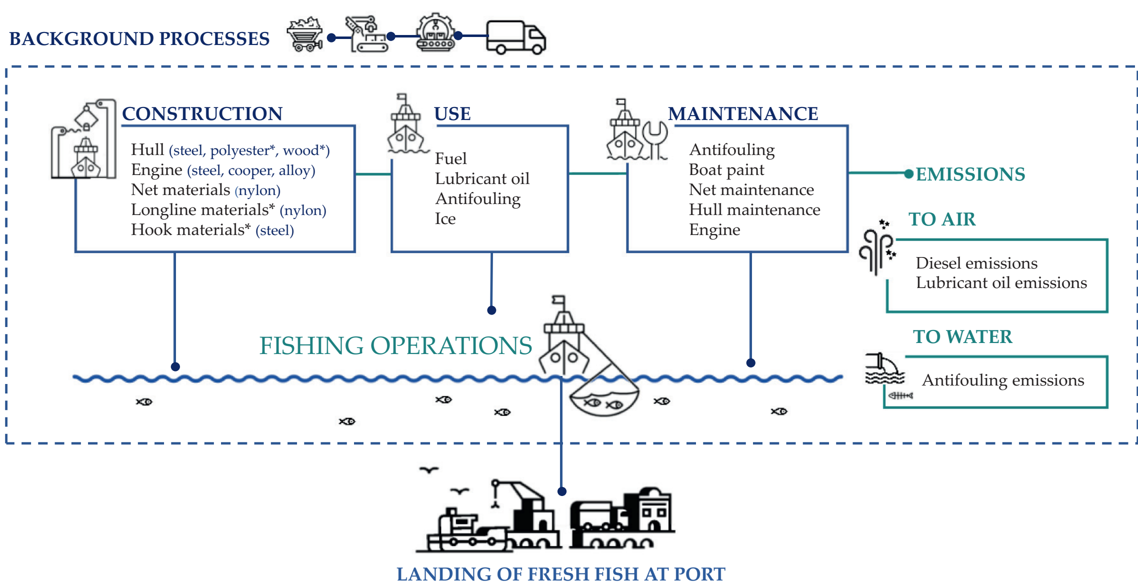


Fig. 3. System boundaries for the Cantabrian fishing fleet composing the 'cradle-to-port' approach. Background processes included raw material extraction, basic processing, manufacturing and transport stages. * Note that longline and hook construction materials were only applicable to minor art vessels using these techniques. In addition, only in the case of some minor art vessels the hull was made of wood or polyester.

Table 1
Average catch value and mass allocation factors for species landed by the Cantabrian purse seine fleet in 2019.

Species	Landings		Mass allocation (%)
	Mass (kg)	SD	
European anchovy (*Engraulis encrasicolus*)	3,993,414	±69,912	37.2
European pilchard (*Sardina pilchardus*)	844,024	±33,485	7.9
Atlantic mackerel (*Scomber scombrus*)	894,474	±15,520	8.3
Atlantic horse mackerel (*Trachurus trachurus*)	1,694,151	±82,505	15.8
Tuna species (mainly *Thunnus alalunga*)	1,692,443	±93,361	15.8
Others	1,625,711	±31,780	15.0

recommended in the PAS 2050 guide (BSI, 2012). The selection of vessels was based on the increased availability of data provided by effective contact with the skippers as not all of them showed interest in participating in the research work.

Primary data were obtained from the Ministry of Rural Development, Fisheries, Food and Environment of the Government of Cantabria (Government of Cantabria, 2022), as well as from a cluster of fishermen working in this community, thus ensuring the reliability of the data and facilitating the completion of a robust life-cycle inventory. Information was collected by means of questionnaires (see Supplementary Materials) delivered to the skippers of ports located in Castro Urdiales (P1), Santoña (P2), Suances (P3), Santander (P4), San Vicente de la Barquera (P5), Comillas (P6) and Colindres (P7). These documents covered a comprehensive identification of the main operational aspects and capital assets of the ships. The specific vessel data requested embraces the overall length, gross tonnage, vessel width, number of engines and their propulsion power, hull material and service life. For each vessel, the operational data demanded included the type and quantity of fuel used, consumption of ice, lubricating oil, antifouling and paint, as well as net use and dimensions. Apart from these, data on the total catches of each species during 2019 were recorded for the mass allocation procedures.

2.5.2. Secondary data

On the other hand, secondary data, i.e., background processes regarding the production of diesel fuel, materials for vessel construction, nets, paint, lubricant and antifouling agents, as well as electricity were added from the Ecoinvent v3.5 (Wernet et al., 2016) and Agribalyse v3.0 (Asselin-Balençon et al., 2020) database (see Table S1). In this regard, market processes (unknown suppliers) were used as default. The choice of process was based on the geographical location closest to Spain and their availability in the database. Thus, the priority in the selection hierarchy was: Spain, Europe, Europe without Switzerland and global.

2.5.3. Assumptions and limitations

Although most of data were obtained directly, it was necessary to adopt a series of assumptions and limitations in order to model some processes.

In terms of ship construction and maintenance, a 30-year service life was assumed, with the exception of the wooden vessels used in artisanal fisheries, which are known to last 40 years (Estrella et al., 2005); with annual maintenance operations, and 12 % of the hull being replaced every two years (Fréon et al., 2014a). Only impacts related to steel used in hulls and engines were quantified by estimating the total ship weight through the light ship weight (LSW) correlation (Eq. (1)), as described by Fréon et al. (2014a). This correlation was considered valid for the Spanish fleet due to the similarity in terms of holding capacity. This way, it was assumed that 80 % and 20 % of the LSW corresponded to the weight of the hull and of the structural elements and other systems not considered in this work, respectively; as was done by Laso et al. (2018b) in an LCA of the Cantabrian purse seine fleet.

$$\text{LSW (t)} = -263.81 + 0.57 \times \text{holding capacity} + 43.77 \times \text{width} \quad (1)$$

To address the construction material for ship hulls, a mixed steel composition including a part of virgin resource and a proportion of recycled steel was considered. Thus, and following the recommendations of the Product Environmental Footprint Category Rules (PEFCR) developed by the European Commission's Joint Research Center (JRC), the steel hull manufacture process was modelled using the Circular Footprint Formula (CFF). This model allows both virgin and secondary steel to be considered. This formula set the guidelines for allocating the environmental burdens or benefits of recycling, reuse or energy recovery between, for example, the supplier and the user of recycled materials (European Commission, 2018). It can be applied to both final products (in a 'cradle-to-grave' approach) and to intermediate products (in a 'cradle-to-gate' approach). In the latter type of studies, the parameters related to the end-of-life () of the product (i.e. recyclability at EoL, energy recovery, disposal) are not accounted for as the system boundaries only cover the impacts from the extraction of raw materials to the time when the product leaves the industry. Herefore, the EoL should be excluded setting the parameters R_2, R_3 and E_d (see equations in Box 1 of Annex A) equal to 0, for in-scope products. Equations for the modelling of 'material + energy + disposal' processes and default values for some parameters specific to steel sheets (A, R_1, R_2*, Q_{sin}/Q_p and Q_{sout}/Q_p) are collected in Annex A, Box 1 and Table A1, respectively.

Regarding the engine, the weight of the main and auxiliary engines was obtained from a leading world producer based on the power data provided by skippers as done by Laso et al. (2018b). To simplify, modelled engines were considered to have a virgin composition of 65 % cast iron, 34 % chrome steel and 1 % white metal alloys (Fréon et al., 2014a), and were replaced once during the vessel lifetime. The CFF formula was not applied to the engine materials as the PEF guidelines does not specify parameters for the materials used. On the other hand, nylon nets had a lifespan of about five years, although 25 % were usually renewed every year due to losses at sea (Vázquez-Rowe et al., 2012a). The amount of paint used during the construction of the vessel was considered to be one third of the amount of antifouling, following the approximation of the ratio of values reported by Vázquez-Rowe et al. (2011). In addition, for the annual maintenance, the consumption of these products was at least equal to that used during the initial preparation. These simplifying assumptions due to a lack of data may introduce a minor amount of error.

With respect to the fishing activity, none of the fishermen interviewed declared to produce their own ice or have an ice-making machine to preserve the fish on board. Instead, ice was provided by fishermen's guilds. Taking a Galician port authority as a reference, an energy consumption of 630 MJ/t was used for the production of ice from tap water in Spain.

Regarding the unmonitored emissions, the impacts resulting from diesel combustion in engines were obtained on the basis of two references: emission factors (EF) for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were based on the IPCC database (IPPC, 2006), whereas EF for sulphur dioxide (SO_2) and other emissions, including particulate matter (PM), nitrogen oxides (NO_x) and heavy metals, among others, were collected from the EMEP-Corinair Emission Inventory Handbook of 2006 (EEA, 2019). Besides, EF for the use of the lubricant oil was obtained from the IPCC. Direct emissions to the water derived from the use of antifouling paint to the marine environment were quantified as a typical loss of two-thirds of the coating that is degraded at the sea (Hospido and Tyedmers, 2005).

Table 2
Average catch value and mass allocation factors for species landed by the Cantabrian minor art fleet in 2019.

Species	Landings		Mass allocation (%)
	Mass (kg)	SD	
Atlantic mackerel (*Scomber scombrus*)	1,827,805	±133,777	21.8
Atlantic horse mackerel (*Trachurus trachurus*)	400,877	±49,100	4.8
Tuna species (mainly *Thunnus alalunga*)	2,440,422	±365,601	29.2
Others	3,696,613	±26,824	44.2

2.5.4. Life cycle inventory (LCI)

LCI involves the compilation of inputs and outputs of the system throughout its life cycle. The primary data revealed that the 17 purse seine vessels landed a total of 10,744 t of fresh fish (considering all fished species) while the 40 minor art vessels landed 8365 t. Tables 1 and 2 above showed the most popular species. The average inventory data per FU are shown in Tables 3 and 4.

2.6. Life cycle impact assessment

The life cycle impact assessment (LCIA) phase is aimed at evaluating the significance of potential environmental impacts using the LCI results by associating energy and material flows with specific environmental impact categories and category indicators. In this research, EF 3.0 method (adapted) (European Commission, 2019) was selected to assess the environmental impacts. A total of seven conventional impact midpoint categories were analysed: Climate change (CC), Photochemical ozone formation (POF), Acidification (AC), Eutrophication—freshwater (EUF), Eutrophication—marine (EUM), Water use (WU), Resource use —fossils (RUF). This method was chosen since it provides a higher degree of specificity and consistency than other methods (Sanyé-Mengual et al., 2022), as well as being suggested by the European Commission for comparison and improvement of the environmental performance of products and companies. The indicators included cover environmental loads to the different protection areas allowing a global perspective of fishing activities, as recommended in fisheries assessment reviews (Avadí and Fréon, 2013). The software SimaPro9.3 (PRé Sustainability, 2021) was used for the computational implementation of the inventories.

It is important to mention that more specific impact indicators were not used for the main drivers of marine biodiversity loss (e.g. seafloor area impact or specific discard indexes (Abdou et al., 2020), as although they are currently used by some LCA practitioners (Vázquez-Rowe et al., 2012b), their methodology is not yet fully developed and standardised, coupled with the fact that there are different levels of uncertainty in terms of hedging of cause-effect pathways and spatial coverage of damage (Woods et al., 2016). This gap in research also encompasses the lack of consideration of the consequences of leaked plastic waste on the environment (Woods et al., 2021).

Moreover, the inclusion of explicit indicators measuring seafloor degradation was not considered of interest since the fishing techniques assessed, purse seine and minor arts, operate at a short distance from the surface, unlike trawling (Buhl-Mortensen and Buhl-Mortensen, 2018). In this way, the expected results would not be significant for the overall analysis of hotspots.

Table 4
Life cycle inventory gathering emissions (diesel, lubricant oil and antifouling) to the environment per FU: 1 kg of fresh fish landed in Cantabrian ports by purse seine and minor art vessels in 2019.

Fishing – emissions to the environment			
		Purse seiners	Minor arts
Emission	Unit	Value	Value
CO_2	kg	$7.96{\cdot}10^{-1}$	$8.53{\cdot}10^{-3}$
CH_4	kg	$7.52{\cdot}10^{-5}$	$5.5{\cdot}10^{-4}$
N_2O	kg	$2.15{\cdot}10^{-5}$	$1.57{\cdot}10^{-7}$
SO_2	kg	$7.54{\cdot}10^{-3}$	$5.53{\cdot}10^{-5}$
NO_X	kg	$1.97{\cdot}10^{-2}$	$1.45{\cdot}10^{-4}$
CO	kg	$1.86{\cdot}10^{-3}$	$1.36{\cdot}10^{-5}$
NMVOC	kg	$7.04{\cdot}10^{-4}$	$5.16{\cdot}10^{-6}$
SO_X	kg	$5.03{\cdot}10^{-3}$	$3.69{\cdot}10^{-5}$
TSP	kg	$3.77{\cdot}10^{-4}$	$2.76{\cdot}10^{-6}$
PM_{10}	kg	$3.77{\cdot}10^{-4}$	$3.27{\cdot}10^{-5}$
$PM_{2.5}$	kg	$3.52{\cdot}10^{-4}$	$2.58{\cdot}10^{-6}$
Pb	kg	$3.27{\cdot}10^{-8}$	$2.40{\cdot}10^{-10}$
Cd	kg	$2.51{\cdot}10^{-9}$	$1.84{\cdot}10^{-11}$
Hg	kg	$7.54{\cdot}10^{-9}$	$5.53{\cdot}10^{-11}$
As	kg	$1.01{\cdot}10^{-8}$	$7.37{\cdot}10^{-11}$
Cr	kg	$1.26{\cdot}10^{-8}$	$9.22{\cdot}10^{-11}$
Cu	kg	$5.03{\cdot}10^{-8}$	$3.69{\cdot}10^{-10}$
Ni	kg	$2.51{\cdot}10^{-7}$	$1.84{\cdot}10^{-9}$
Se	kg	$2.51{\cdot}10^{-9}$	$1.84{\cdot}10^{-11}$
Zn	kg	$3.02{\cdot}10^{-7}$	$2.21{\cdot}10^{-9}$
PCB	kg	$9.55{\cdot}10^{-12}$	$7.00{\cdot}10^{-14}$
PCDD/F	μg I-TEQ	$3.27{\cdot}10^{-5}$	$2.40{\cdot}10^{-7}$
HCB	kg	$2.01{\cdot}10^{-11}$	$1.47{\cdot}10^{-13}$

On the other hand, although the Abiotic depletion indicator (MJ), which embrace the impacts derived from the use of fossil fuels, was not selected, an exhaustive analysis of diesel consumption was carried out in the results. Fuel efficiency or Fuel Use Intensity (FUI) constitute indicators for environmental effects of fishing vessels according to European Commission (STECF, 2020). FUI is usually measured in terms of L of fuel per tonne of fish landed but, in this study, it was translated into kg of diesel per FU.

3. Results

3.1. Environmental performance of Cantabrian fisheries—global indicators

According to the results shown in Table 5, purse seine fishing had global higher impacts than minor art techniques for all indicators, except for EUF,

Table 3
Life cycle inventory gathering average inputs per FU: 1 kg of fresh fish landed in Cantabrian ports by purse seine and minor art vessels in 2019.

Vessel construction and maintenance – inputs from technosphere					
Material	Unit	Purse seiners		Minor arts	
		Construction	Maintenance	Construction	Maintenance
Steel (hull)	kg	$8.09{\cdot}10^{-3}$	$4.85{\cdot}10^{-4}$	$3.00{\cdot}10^{-4}$	$1.80{\cdot}10^{-5}$
Wood (hull)	kg	–	–	$1.80{\cdot}10^{-4}$	$1.08{\cdot}10^{-5}$
Polyester (hull)	kg	–	–	$7.19{\cdot}10^{-4}$	$4.32{\cdot}10^{-5}$
Cast iron (engine)	kg	$1.98{\cdot}10^{-4}$	$1.65{\cdot}10^{-4}$	$9.00{\cdot}10^{-5}$	$6.38{\cdot}10^{-5}$
Chrome plating steel (engine)	kg	$1.04{\cdot}10^{-4}$	$8.61{\cdot}10^{-5}$	$4.71{\cdot}10^{-5}$	$3.34{\cdot}10^{-4}$
White metal alloy (engine)	kg	$3.05{\cdot}10^{-6}$	$2.53{\cdot}10^{-6}$	$1.38{\cdot}10^{-6}$	$9.82{\cdot}10^{-7}$
Paint	L	$6.81{\cdot}10^{-5}$	$1.74{\cdot}10^{-4}$	$1.92{\cdot}10^{-4}$	$1.92{\cdot}10^{-4}$
Antifouling	L	$3.44{\cdot}10^{-4}$	$3.44{\cdot}10^{-4}$	$9.44{\cdot}10^{-4}$	$9.44{\cdot}10^{-4}$
Nets	p	$4.56{\cdot}10^{-6}$	$2.51{\cdot}10^{-7}$	$7.46{\cdot}10^{-5}$	$1.86{\cdot}10^{-5}$
Nylon (longline)	kg	–	–	$1.38{\cdot}10^{-4}$	$3.46{\cdot}10^{-5}$
Hooks	p	–	–	$6.11{\cdot}10^{-3}$	–

Fishing – inputs from technosphere			
		Purse seiners	Minor arts
Diesel	L	$2.51{\cdot}10^{-1}$	$7.37{\cdot}10^{-2}$
Lubricant oil	L	$1.60{\cdot}10^{-3}$	$4.09{\cdot}10^{-4}$
Ice	kg	$3.44{\cdot}10^{-1}$	$1.27{\cdot}10^{-1}$

Table 5
Environmental impact indicators of EF 3.0 method (adapted). Values represent the average results per FU for the total fleet considered—Global activity.

	Unit	Purse seine (PS)	Minor arts (MA)
		Value	Value
Climate change (CC)	kg CO_2 eq.	1.00	0.34
Photochemical ozone formation (POF)	kg NMVOC eq.	$2.19·10^{-2}$	$6.52·10^{-3}$
Acidification (AC)	mol H^+ eq.	$2.32·10^{-2}$	$7.10·10^{-3}$
Eutrophication—freshwater (EUF)	kg P eq.	$7.38·10^{-6}$	$1.15·10^{-5}$
Eutrophication—marine (EUM)	kg N eq.	$7.93·10^{-3}$	$2.38·10^{-3}$
Water use (WU)	m^3 depriv.	$6.23·10^{-2}$	$4.89·10^{-2}$
Resource use—fossils (RUF)	MJ	14.25	5.07

where artisanal fishing reached $1.15·10^{-5}$ kg P eq. versus the $7.38·10^{-6}$ of purse seine. This could be due to the higher use of antifouling agents reported in the minor arts. Regarding the individual results for each stage (Table 6), the use stage stood as the main carrier of environmental burdens for CC ($9.50·10^{-1}$ and $2.80·10^{-1}$ kg CO_2 eq.), POF ($2.17·10^{-2}$ and $6.37·10^{-3}$ kg NMVOC eq.), AC ($2.29·10^{-2}$ and $6.73·10^{-3}$ mol H^+ eq.), EUM ($7.86·10^{-3}$ and $2.31·10^{-3}$ kg N eq.) and RUF ($1.36·10^{+1}$ and 4.02 MJ). By contrast, maintenance was the main contributor to EUF whereas construction was determinant for WU indicator. These trends are common for both fishing sorts. In terms of magnitude, minor art fishing had greater values than purse seine for six out of seven indicators when analysing the construction stage. However, when it comes to the maintenance stage, purse seine achieved higher loads in five of the seven impact categories. Finally, during the use phase purse seine activities performed the worst.

3.2. Environmental performance of Cantabrian fisheries—critical resources

As abovementioned, vessel use was the main phase contributing to most impact categories. Thus, when examining the results deeply (Fig. 4a and b), diesel use was the main critical resource for all impact categories, except for WU and EUF. For the rest indicators, its contribution was in all cases above 75 %, reaching even values higher than 98 %. It is worth mentioning that these results were quite similar in purse seine and minor art fishing. Furthermore, when diesel use is excluded from these indicators where it accounts for almost the entire impact, it was observed that purse seine nets accounted for 13–47 % of the total loads measured. The steel used for the construction and maintenance of the purse seine vessel hull was responsible on average for between 15 and 30 % of the remaining impacts and ice consumption showed also relevant percentages (25–30 %). The other resources not mentioned exhibited insignificant contributions (<5 %, in general). On the other hand, when looking at minor art fleet results in detail (also excluding diesel consumption), the average number of hooks used in longline practices were the main carrier with more than half of the total impacts in most categories. Ice and antifouling consumption also generated small impacts (~10 % on average).

In relation to WU and EUF categories, impacts were commonly distributed between purse seine nets (32–42 %) and hull steel (10 %). Ice consumption (41.5 %) was significant for WU in purse seine activities and antifouling was responsible for 40 % of freshwater eutrophication. For the artisanal fishing fleet, hooks accounted for 66.8 % and 24.7 % of the impacts measured in WU and EUF, respectively. Ice consumption had some relevance in WU (20.3 %) while antifouling was the main carrier of environmental loads for EUF, similar in this case to the results obtained for purse seiners.

4. Discussion

4.1. Identification of environmental hotspots

Regarding the impacts on CC, this study found that purse seiners showed a quantity of 1.00 kg CO_2 eq. per kg of whole fish landed, whereas the amount emitted by the minor art fleet was almost a third (0.34 kg CO_2 eq. per kg of whole fish landed). These figures were consistent with the expected results for pelagic fisheries, which were found to have the lowest carbon footprint (Hognes et al., 2011), typically around or below 1 kg CO_2 eq. per kg of whole fish landed. Some examples of studies addressing these species were the one focusing on the Scottish pelagic trawl fleet, with a CC value equal to 0.452 kg CO_2 eq. (Sandison et al., 2021), the one analysing the Indian bottom trawl fleet, with 0.99 kg CO_2 eq. (Devi et al., 2021); or the one managing the purse seine fishery in Portugal, with 0.36 kg CO_2 eq. (Almeida et al., 2014).

Going a step further and comparing the carbon footprint of pelagic fisheries with that of other species, and even with that of land-based animal production, there is evidence that pelagic species stand out as one of the most efficient and low-carbon types of animal protein available (Parker et al., 2018). Examples illustrate that GHG emissions from pelagic fisheries, especially those classified as 'small pelagic', were significantly lower than those from aquaculture products, and also much lower than the impacts of livestock farming, with beef production estimated to have >20 times higher impacts (Hilborn et al., 2018).

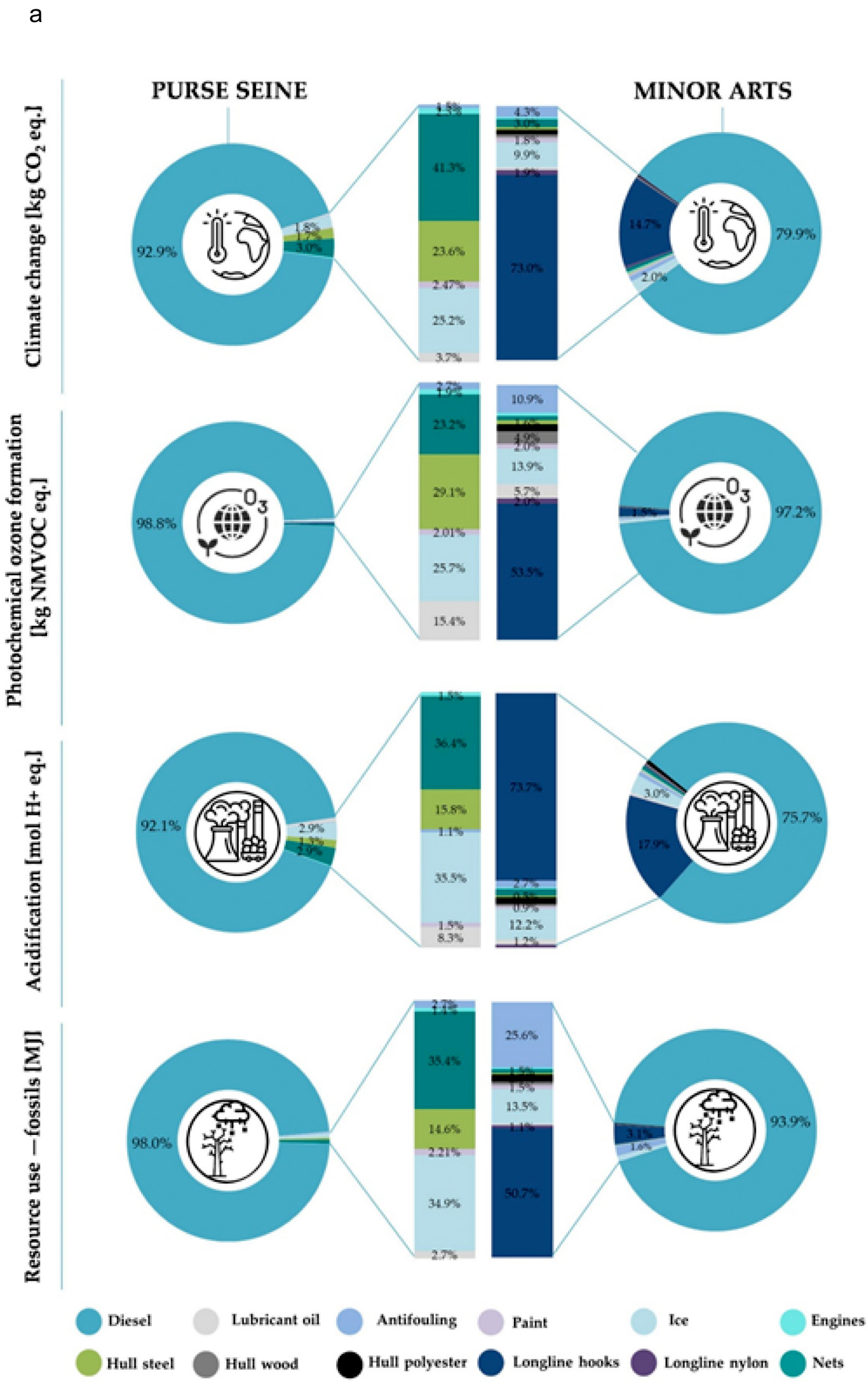
For POF, AC and RUF, these indicators were found to follow the trends discussed in the CC, leading to the conclusion that the major focus for improving the overall environmental performance of fisheries should be put on fuel efficiency. In terms of water degradation, EUM was due to the use of diesel while EUF appeared to be strongly related to antifouling use, probably due to copper and zinc emissions, as suggested by existing literature. Moreover, it should be noted that corrosion of ships is an unexplored impact in LCA studies of seafood that may cause certain environmental impacts, especially in terms of ecotoxicity (Laso et al., 2018b).

4.2. Fuel use intensity (FUI)

The results obtained for the Cantabrian purse seine and minor art fishing fleet have allowed the use of diesel (production, transport and direct

Table 6
Environmental impact indicators of EF 3.0 method (adapted). Values represent the average results per FU for the total fleet considered—individual stages.

	Unit	Construction		Maintenance		Use	
		Purse seine	Minor arts	Purse seine	Minor arts	Purse seine	Minor arts
CC	kg CO_2 eq.	$4.11·10^{-2}$	$5.60·10^{-2}$	$1.06·10^{-2}$	$5.02·10^{-3}$	$9.50·10^{-1}$	$2.80·10^{-1}$
POF	kg NMVOC eq.	$1.25·10^{-4}$	$1.20·10^{-4}$	$3.16·10^{-5}$	$2.59·10^{-5}$	$2.17·10^{-2}$	$6.37·10^{-3}$
AC	mol H^+ eq.	$1.94·10^{-4}$	$2.50·10^{-4}$	$8.92·10^{-5}$	$1.21·10^{-4}$	$2.29·10^{-2}$	$6.73·10^{-3}$
EUF	kg P eq.	$2.68·10^{-6}$	$3.06·10^{-6}$	$3.57·10^{-6}$	$8.08·10^{-6}$	$1.13·10^{-6}$	$3.92·10^{-7}$
EUM	kg N eq.	$4.83·10^{-5}$	$5.62·10^{-5}$	$1.64·10^{-5}$	$1.31·10^{-5}$	$7.86·10^{-3}$	$2.31·10^{-3}$
WU	m^3 depriv.	$2.83·10^{-2}$	$3.57·10^{-2}$	$7.88·10^{-3}$	$3.53·10^{-3}$	$2.61·10^{-2}$	$9.71·10^{-3}$
RUF	MJ	$5.13·10^{-1}$	1.00	$1.30·10^{-1}$	$5.70·10^{-2}$	13.6	4.02


a
PURSE SEINE
MINOR ARTS
Climate change [kg CO2 eq.]
92.9%
79.9%
14.7%
41.3%
23.6%
25.2%
73.0%
Photochemical ozone formation [kg NMVOC eq.]
98.8%
97.2%
23.2%
29.1%
25.7%
15.4%
10.9%
13.9%
53.5%
Acidification [mol H+ eq.]
92.1%
75.7%
17.9%
36.4%
15.8%
35.5%
8.3%
73.7%
12.2%
Resource use —fossils [MJ]
98.0%
93.9%
35.4%
14.6%
34.9%
25.6%
13.5%
50.7%
Diesel
Lubricant oil
Antifouling
Paint
Ice
Engines
Hull steel
Hull wood
Hull polyester
Longline hooks
Longline nylon
Nets

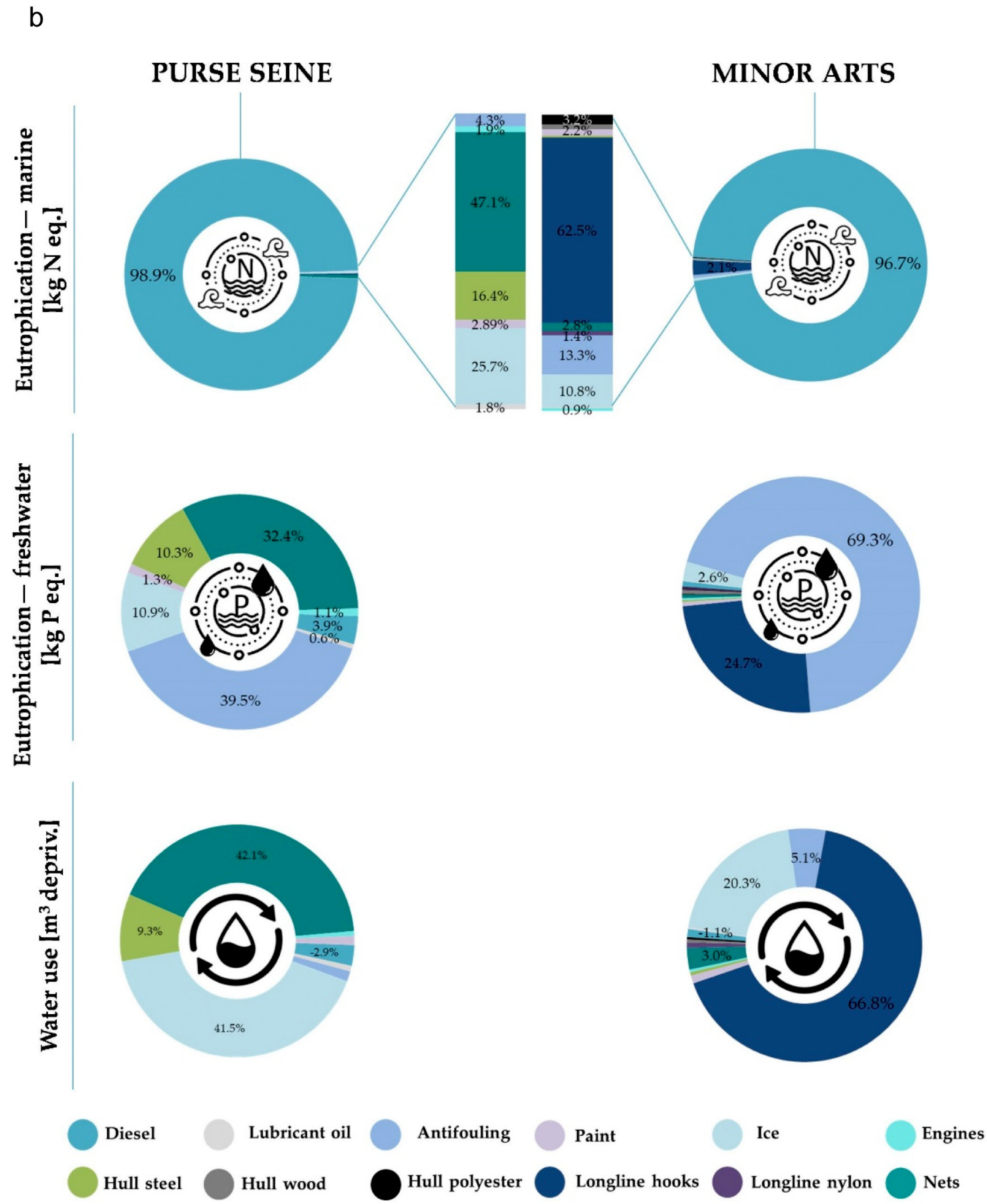


Fig. 4. a and b Contribution of resources to total environmental impact indicators of EF 3.0 method (adapted). Values represent the average results per FU for the total fleet considered.

combustion, including emissions) to be identified as the main resource generating the greatest environmental impacts for the vast majority of the indicators used. This is not a new finding, as most studies on the fishing sector have revealed that the direct use of fuel in the vessel represents the main carrier of detrimental environmental impacts (Avadí and Fréon, 2013), accounting for between 60 % and 90 % of the total life cycle GHG emissions (Granado et al., 2021).

Some authors have tried to quantify the global FUI. Parker et al. (2018) estimated a consumption of 0.44 kg fuel per kg catch, and Greer et al. (2019) approximated to a value of 0.59. The average results of this research revealed that purse seiners had a fuel usage of 0.25 kg of fuel per kg of fish landed (considering pelagic landings as a whole), while the performance of the minor art fleet showed a significant lower consumption of 0.07 kg of fuel per kg of fish landed. These outcomes are in the range of values available in current literature (Bastardie et al., 2022). It is worth mentioning that the comparison between studies is not straightforward as literature suggests that FUI varies greatly between fisheries targeting different species, employing different gears and vessels with distinct characteristics, as well as fishing in disparate regions using diverse strategies (Chassot et al., 2021). Small pelagic fisheries are broadly regarded to be one of the lowest impact fisheries, with purse seining usually highlighted as the most fuel-efficient fishing method (Sandison et al., 2021), especially when compared

Table 7
Diesel consumption per FU of other pelagic species fisheries reported in the literature.

Species	Fishing art	Value [kg diesel/FU]	Reference
Pelagic species	Purse seine	0.25	Current study
Pelagic species	Minor arts	0.07	Current study
Tuna	Purse seine	1.59	Current study
Tuna	Minor arts	0.25	Current study
European anchovy	Purse seine	0.67	Current study
Small pelagic species	Trawl	0.35	Jafarzadeh et al. (2016)
Pelagic species	Coastal seine	0.05	Jafarzadeh et al. (2016)
Pelagic species	Trawl	0.04	Sandison et al. (2021)
Tuna	Purse seine	0.32	Parker et al. (2015)
Tuna	Longline	0.95	Parker et al. (2015)
Tuna	Purse seine	0.28	McKuin et al. (2021)
Tuna	Purse seine	0.77	Avadí and Fréon (2015)
European anchovy	Purse seine	0.34	Laso et al. (2018b)
Peruvian anchoveta	Purse seine	0.01	Fréon et al. (2014b)

to higher trophic level species caught by trawl or longline (Parker and Tyedmers, 2015), even though the improved efficiency of mid-water trawling as compared to bottom trawling (Ruiz-Salmón et al., 2021b). In fact, bottom trawling was found to be one of the most fuel-intensive fishing methods (Hognes et al., 2011; Schau et al., 2009), up to five times less efficient than purse seining in some cases. Table 7 shows some references from literature. Jafarzadeh et al. (2016) reported a value of 0.35 kg fuel/kg small pelagic landed using trawls, in addition to a consumption of only 0.05 kg fuel/kg fish landed by coastal seine methods, in opposite with the findings of (Sandison et al., 2021) and (Furuya et al., 2011), who obtained a FUI of 0.04 and 0.08 using trawls for the capture of pelagic species. In the Avadí and Fréon (2013) review the kg fuel/kg of small pelagic fish with purse seine was equal to 0.07.

Worldwide studies on FUI are mainly concerned with species-specific fisheries. In this line there are different claims for tuna fisheries, with consumptions ranging from 0.28 to 0.77 using purse seiners (Avadí and Fréon, 2015; McKuin et al., 2021), to values of 0.95 when longline is used (Parker et al., 2015). In the case of other species, such as anchovy catches by purse seine, the use of diesel per FU is 0.34 (Laso et al., 2018b), somewhat higher than that recorded for Peruvian anchoveta (0.01) (Fréon et al., 2014a). To obtain species-specific FUI values, a mass allocation following the percentages of Tables 1 and 2 was applied, so that the diesel consumptions were distributed based on the proportion of each species in the total catch weight (see Table 7). Thus, figures of 0.25 and 1.59 kg of diesel per kg of tuna landed were estimated using minor arts and purse seiners, respectively. Additionally, European anchovy in purse seiners showed an uptake of 0.67 kg diesel/FU. The first impression appeared to be that the purse seine consumptions obtained for specific species were slightly higher than those available in the literature. Notwithstanding, it should not be forgotten that these numbers are the result of a mass allocation, so they should be viewed with caution. From the different results obtained in this study for the same species, and from the comparison with existing literature, it can be generalised that energy efficiency in relation to fuel use is highly dependent on the fishing gear used.

Ultimately, oil consumption is subjected to complex factors often unaccounted for. These include the natural abundance of the resource, the stock status, the spatio-temporal variability of catchability –level of aggregation, depth and distance from shore– the skill level of the vessel's crew –the 'skipper effect' (Vázquez-Rowe and Tyedmers, 2013) – and the proportion of by-catch or hull technology.

In this respect, decarbonisation must now be considered a top priority for shipping organisations. Decarbonisation of marine fuels is key to meeting the GHG reduction target set by the International Maritime Organization (IMO), for which mandatory measures were adopted under IMO's pollution prevention treaty (MARPOL), the mandatory Energy Efficiency Design Index (EEDI) for new ships, as well as the Ship Energy Efficiency Management Plan (SEEMP), which aims to promote the use of more energy-efficient engines (International Maritime Organization, 2020). What is more, the European Commission developed in 2015 the MRV regulation on 'monitoring, reporting and verification of CO_2 emissions from maritime transport', whose target is to reduce the carbon footprint (CF) of maritime transport (European Commission, 2015). All these benchmarks focus on pollution from conventional propulsion systems, which use gasoline or diesel as fuel, and their related equipment. Nevertheless, a number of measures are currently being developed to implement promising alternatives to conventional fuels, promoting the transition to green transport. In this regard, the European Commission's Hydrogen Strategy for a climate-neutral Europe (European Commission, 2020b) sets out a series of strategies based on regulation, investment, research, and innovation to promote decarbonisation in industry, transport, and power generation in Europe, using H_2 as an energy carrier (Fernández-Ríos et al., 2022). Cantabria's fleet of fishing ships should focus its efforts on following these decarbonisation lines in order to improve its environmental performance.

5. Conclusions

The purse seine and artisanal fleet operating in Cantabria represents an emblematic and high added- value fishery that supports a large part of the region. The objective of this study was to assess for the first time the overall environmental performance using a sample of a total of 57 vessels, representing more than half of the Cantabrian fleet.

The LCA outcomes revealed that diesel use was the main carrier of environmental burdens for most conventional impact categories whereas the use of antifouling paints stood as a hotspot in freshwater eutrophication due to emissions of metallic compounds included in its formulation. The remaining activities showed lower relative contributions. Similar trends were observed for purse seine and minor art vessels. Overall, small pelagic fisheries are competitive in terms of carbon footprint and energy use, both in comparison to other seafood products and to land-based animal proteins.

The fact that fuel use usually varies so much between fishing activities, coupled with the significant environmental cost and volatility of fuel prices, underlines the need for further examination to better understand the factors driving those differences. There is great potential to reduce even more GHG emissions by selecting the most efficient techniques for each target species, as this can have a major impact on the fishing industry and on contributing to climate-smart and sustainable food production systems.

These LCA results are a key tool for effectively communicating the relative environmental costs and benefits of product choices to consumers.

Finally, it could be concluded that this type of work would be facilitated by improving data availability through the introduction of traceability systems in the seafood supply chain and energy recording systems on fishing vessels.

To sum up, it is scientifically proven that the use of fossil fuels represents the greatest environmental impacts in fishing activities, so future efforts should focus on investigating the potential replacement of traditional combustion engine-powered vessels with new low-emission ones powered by green and renewable technologies, such as electric or hybrid engines. Sustainable mobility is already well established in the road vehicle fleet, so now it is time for its implementation to reach the ocean.

Abbreviations and acronyms

AC Acidification
BSI British Standards Institution
CC Climate Change
CEAP Circular Economy Action Plan
CEPESCA Confederación Española de Pesca

CFF	Circular Footprint Formula
Clúster MARCA	Clúster Marítimo de Cantabria
CNW	Cantabrian and Northwest
EEA	European Environmental Agency
EF	Emission Factors
EoL	End of Life
EU	European Union
EUF	Eutrophication—freshwater
EUM	Eutrophication—marine
EUMOFA	European Market Observatory for Fisheries and Aquaculture
FAO	Food and Agriculture Organization
FU	Functional Unit
FUI	Fuel Use Intensity
GDP	Gross Domestic Product
GHG	Greenhouse Gas
ICANE	Instituto Cántabro de Estadística
IMO	International Maritime Organization
IPPC	Integrated Pollution Prevention and Control
ISO	International Organization for Standardization
IUU	Illegal, Unreported and Unregulated
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSW	Light Ship Weight
MA	Minor arts
MAPA	Ministerio de Agricultura, Pesca y Alimentación
MPs	Microplastics
NMVOC	Non-Methane Volatile Organic Compounds
OPECA	Organización de Productores de Pesca de Altura de Cantabria
PCDD/F	Polychlorinated Dibenzo-p-Dioxins/Furans
POF	Photochemical Ozone Formation
PS	Purse seine
R&D&I	Research, Development and Innovation
RUF	Resource use—fossils
SDG	Sustainable Development Goal
STECF	Scientific, Technical and Economic Committee for Fisheries
WU	Water Use

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CRediT authorship contribution statement

Sandra Ceballos-Santos: Methodology, Investigation, Software, Validation, Formal analysis, Data curation, Writing – original draft, Visualization. **Jara Laso:** Conceptualization, Software, Formal analysis, Methodology, Data curation, Investigation, Visualization, Validation, Writing – review & editing. **Laura Ulloa:** Writing – review & editing, Visualization, Validation. **Israel Ruiz Salmón:** Software, Data curation, Investigation, Methodology, Visualization, Validation. **María Margallo:** Data curation, Writing – review & editing, Supervision, Visualization, Validation. **Rubén Aldaco:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition, Visualization, Validation.

Data availability

Data will be made available on request.

Declaration of competing interest

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

Annex A

Box 1
Circular Footprint Formula (CFF).

The CFF is a combination of 'material + energy + disposal':

Material

$$(1-R_1)E_v + R_1 \times \left(AE_{recycled} + (1-A)E_v \times \frac{Q_{sin}}{Q_p}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E_v^* \times \frac{Q_{Sout}}{Q_p}\right)$$

Energy

$$(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,\ heat} \times E_{SE,\ heat} - LHV \times E_{ER,\ elec} \times E_{SE,\ elec})$$

Disposal

$$(1-R_2-R_3) \times E_D$$

Parameters of the CFF:

A: allocation factor of burdens and credits between supplier and user of recycled materials.

B: allocation factor of energy recovery processes. It applies both to burdens and credits.

Q_{sin}: quality of the ingoing secondary material, i.e., the quality of the recycled material at the point of substitution.

Q_{sout}: quality of the outgoing secondary material, i.e., the quality of the recyclable material at the point of substitution

Q_p: quality of the primary material, i.e., quality of the virgin material.

R_1: it is the proportion of material in the input to the production that has been recycled from a previous system.

R_2: it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore consider the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.

R_3: it is the proportion of the material in the product that is used for energy recovery at EoL.

$E_{recycled}$ (E_{rec}): specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting, and transportation process.

$E_{recyclingEoL}$ (E_{recEoL}): specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting, and transportation process.

E_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.

E^*_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

E_{ER}: specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g., incineration with energy recovery, landfill with energy recovery, etc.).

$E_{SE,heat}$ and $E_{SE,elec}$: specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.

E_D: specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.

$X_{ER,heat}$ and $X_{ER,elec}$: the efficiency of the energy recovery process for both heat and electricity.

LHV: lower heating value of the material in the product that is used for energy recovery.

Table A1
Circular Footprint Formula default values (A, R_1, R_2, Q_{sin}/Q_p and Q_{sout}/Q_p).

Category	Material	Application	Parameters				
			A	R_1	R_2*	Q_{sin}/Q_p	Q_{sout}/Q_p
Metals	Steel	Building-sheet	0.2	0.18	0.95	1	1

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