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From the sea to the table

The environmental impact assessment of fishing, processing, and end-of-life of albacore in Cantabria

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Abstract

Cantabria, a small coastal region of Northern Spain, is one of the biggest producers of gourmet tuna cans in Europe. The fish capture in the Cantabrian Sea and the subsequent transformation in a local processing plant give distinction to this product, which is widely marketed in cans of 105 g of net weight. This work evaluates for the first time the environmental profile of the whole supply chain of this product, from fishing, processing, and waste valorization to inter-stage transport and packaging management in the end-of-life. To this end, the life cycle assessment methodology was applied considering primary data from the stakeholders involved in the supply chain and analyzing the seven most studied categories in this sector. Results revealed that fishing and processing accounted for the majority of the environmental impacts, while valorization and end-of-life treatments only avoid less than 10% of the burdens. The most important findings are focused on the high dependence on fuel use, identified as a hotspot in most stages although low compared to other fisheries, and on the intensive use of resources, especially sunflower oil, which contributes more than 70% of the impact on the global warming potential of the processing. This current framework forces the enhancement of the efficiency of a sector that attempts to engage the challenge of societal sustainability, by identifying the critical points and guiding policy makers on the path to sustainable development.

KEYWORDS
canning, circular economy, fisheries, life cycle assessment, tuna

1 | INTRODUCTION

The economy and cultural heritage of Cantabria, a coastal region of Northern Spain, has been traditionally based on the primary sector, highlighting fish and seafood products (Areizaga et al., 2012). Although the weight of this activity is far from the weight of the industry or the service sector in terms of gross domestic product (GDP), the landed catches are continuously growing, reaching 25,000 tonnes of auctioned fishing in 2019, and valued at 47.6 million euros (ICANE, 2021b). Anchovy, tuna, hake, mackerel, horse mackerel, and sardine are the main species captured, and artisanal fishing and purse seine are the most extended fishing gears in Cantabria, representing around 50% and 30% of the total fleet, respectively (BOC, 2001).

In particular, tuna (*Thunnus alalunga*), known as albacore, is commercialized as "Bonito del Norte" when the species is captured in the Cantabrian Sea (Bay of Biscay Fishing Subarea (27.8)) (FAO, 2021a). The capture mainly takes place when tuna migrates from Azores to the Cantabrian Sea costs at the end of spring and the *costera*, the albacore campaign, which places Spain, the fourth largest producer in the world (6.5% of production), behind Japan (20.9%), Taiwan (19.4%), and China (12.1%) (MAGRAMA, 2017). According to the Government of Cantabria, the largest amount of albacore is landed by 34 purse seine vessels, although 45 minor arts vessels are also dedicated to the fishing of tuna.

The relevance of the manufactured seafood products, such as canning, is growing over the last decade, and currently 10% of the catches are intended for the processing industry, which provides higher value-added products (ICANE, 2021a). In fact, anchovies and tuna occupy the top #2 and #3 of the all kind Industrial Products Survey in the Eastern Coastal area of Cantabria with 5990 and 6328 tonnes of production and 80.6 and 60 million euros, respectively (ICANE, 2021b). Besides its economic and social importance, fresh and processed marine products are greatly present on the established Atlantic diet of the community, with 23.13 kg of fish consumed per person and year, higher than the national average (22.53) (MAPA, 2020).

The seafood sector is crucial for some Atlantic regions and its sustainable development requires the analysis of the impacts associated with the activity. Life cycle assessment (LCA) has been applied to different stages of the sector, especially to the fisheries, including different species and fishing gears. Not in vain, most of the LCA studies on fisheries have been developed in Spain, mainly in the Atlantic–Cantabrian coast (Ruiz-Salmón et al., 2021). Tuna fishing and processing have received important attention in the past, particularly relevant by LCA practitioners since 2000s. Hospido and Tyedmers (2005) reported the environmental impacts associated with the fisheries until the unloading of frozen tuna in Galician harbors, considering a "cradle to gate" approach, only covering the capture of skipjack tuna (*Katsuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*). Similarly, Parker et al. (2015) studied the global purse seine tuna fleet of four species—skipjack, yellowfin, albacore, and bigeye (*Thunnus obesus*). Hospido et al. (2006) continued with the post-landing activities of *T. albacares*, from transport harbor factory to consumption in households, this is, a "gate to cradle" view. Avadí et al. (2015) focused the research in both the fisheries and processing of Ecuadorian tuna yellowfin, skipjack, and bigeye and, recently, Cortés et al. (2021) considered the capture and manufacture of skipjack tuna, including the valorization of fish waste derived from canning. In summary, to date all tuna studies have addressed one or more stages of the life cycle, but not in its entirety.

The present work goes a step beyond addressing the whole life cycle of tuna: the capture in the Cantabrian coasts, the transformation into a final multi-ingredient processed product in a canning factory, the distribution to the sales centers, and both the valorization of wastes for fishmeal and fish oil production and the disposal and final treatment of the packaging after consumption. Thus, a "cradle to grave" approach is applied for the first time to the tuna species, having in mind overviews reported for flatfish (Thrane, 2006), mussels (Iribarren et al., 2010), hake (Vázquez-Rowe et al., 2011), or anchovy (Laso et al., 2017). This advance provides detailed knowledge of the most critical, polluting, and resource-consuming stages of the seafood sector, which serves as a basis for proposing improvements and outlining actions and policies aimed at enhancing the sustainability of fishing activities, expanding the target audience not only to LCA practitioners but also involving and assisting producers, processing industry managers, and even consumers in decision-making processes.

2 | METHODS

2.1 | Goal and scope

According to the methodology established by the UNE-EN ISO 14040 and 14044 standards (ISO, 2006a, 2006b), any LCA study must include the goal and scope definition. The main goal was to develop a thorough environmental analysis of the production of canned tuna with sunflower oil. To the best of our knowledge it is the first "cradle to grave" LCA article assessing this specific product, based on actual data of Cantabrian fishing fleets and a processing plant located in the East of the region. The outcomes lead to the identification of the chief hotspots along the product whole life cycle, allowing the proposal of potential improvements and measures, and fostering the transition toward a more sustainable fishing sector.

The overall function of the system is the production of canned tuna; consequently, the FU must reflect this purpose. The most common functional unit (FU) for environmental assessments of foods are weight-based functional unit (WBFU), energy-based functional unit (EBFU), and nutrient-based functional unit (NBFU) (McAuliffe et al., 2020). The former is the largest applied, usually providing the impacts per 1 kg, 1 tonne, or per equivalent weight of a saleable product, whereas the latter two consider nutritional aspects, expressing the burdens per kcal (EBFU), or per g of nutrient, commonly protein (NBFU). In this case, an FU of a can of 105 g of net weight of tuna in sunflower oil (75 g tuna and 30 g of oil) was selected. It is considered the appropriate FU for two main reasons. On the one hand, a WBFU provides the most understandable reference since it considers a physical variable. Indeed, it allows its conversion to other FUs for more appropriate comparisons between products. This feature is of great interest considering the target audience, both LCA practitioners and citizens, who require easily assimilable information without the need for great technical knowledge (FAO, 2021b). Furthermore, nutritional aspects were not considered in this study, so the application of an EBFU or

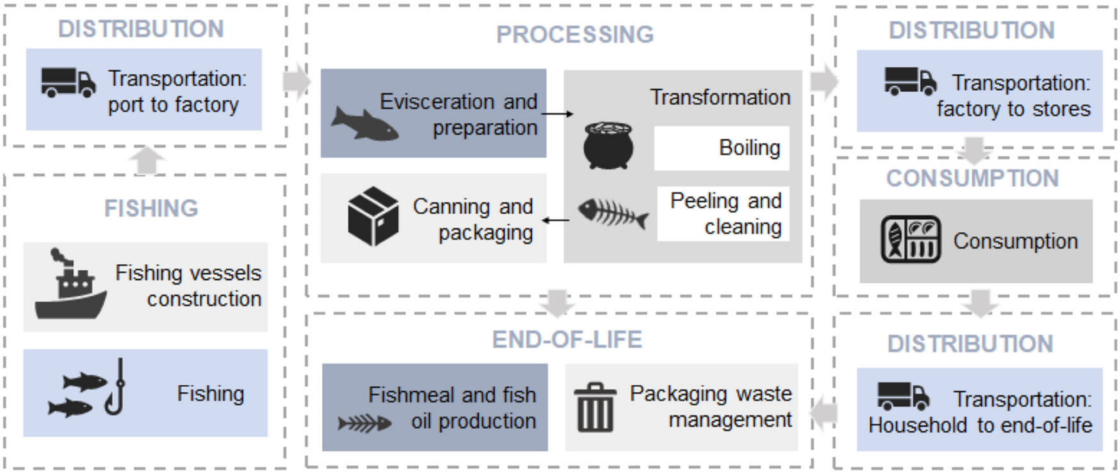

FIGURE 1 Flow diagram of the system under study

NBFU would lead to confusing outcomes and interpretation. On the other hand, it consists of a saleable food, so an FU of equivalent weight of the item may seem suitable in order to provide consumers with environmental information of the product by means of eco-labeling. The processing plant offers several types of products, including tuna in sunflower oil, in AOVE (extra virgin olive oil), or unprocessed (natural), as well as different packaging materials (aluminum or glass) and formats (Dingley, Bol, Hansa, or jar). A can of Dingley format with sunflower oil was established as FU since its production accounts 50% of the total.

Consistently with the goal, a "cradle to grave" approach was considered, as Figure 1 illustrates. According to the processing factory, around 80% of the species are fished in the costs near Cantabria. Although fish distribution from the harbors to the canning factory could be considered negligible because takes places in the same small region, it was included to link each stage with the following. Thus, the product distribution to stores and the transport of the packaging wasted in households to the EoL management were also addressed. In fishing, production and use of nets, engines, paint, antifouling, diesel, and other resources for vessels construction, maintenance, and operation were considered. The transformation takes place in a processing plant located in the Northeast of Cantabria, including all operations transforming fresh tuna into the packed product. First, cutting, evisceration, and preparation of the fish is carried out for subsequent cooking in brine. Once boiled, tuna is peeled and cleaned to remove bones and skin. The resulting fish is canned in tin, glass, or aluminum containers together with sunflower oil, which are hermetically sealed and sterilize to preserve the quality of the product. Finally, the goods are packaged in a cardboard folding (secondary packaging) and cardboard box (tertiary) for distribution to stores. Heads, bones, skins, viscera, and other organic waste are used to obtain by-products, that is, fish oil and fishmeal, with the aim of taking advantage of the waste. The valorization process starts with the separation of the liquid (oils) and solid (cake) fractions. The cake goes through a homogenizer, a dryer, and subsequent grinding to obtain fishmeal, while the oils are subjected to centrifugation, evaporation, and another centrifugation to eliminate impurities and obtain the final product. The use of different reagents such as bactericide or antioxidant is necessary. On the other hand, the management of cans and secondary packaging is carried out by means of recycling, incineration, or landfilling.

It is worth mentioning that a mass allocation was applied to fishing because the fleet captured a multitude of species, representing tuna an average of 17% per vessel and a maximum of 47%. Despite the suitability of considering a system expansion instead of allocations, this option was rejected due to the large number of species resulting from the fishery and their multiple possible applications or uses. In addition, this article focuses on the complete life cycle of a specific species, tuna, and a specific processed product, canned Bonito del Norte with sunflower oil, so including possible utilization scenarios for the remaining species may take us away from the proposed objective, expanding the scope and boundaries of the system substantially. Besides, a mass allocation was also used to obtain the environmental impacts of the Dingley format among several products targeted in the canning plant. On the contrary, a system expansion was considered in the valorization stage: the valorization of tuna residues was substituted by the production of oil and fishmeal from fresh product (1:1). Thus, the modeling allowed the calculation of the avoided burdens associated (Avadí & Freón, 2014). In this case, the study of a system expansion is justified by the great potential of fish waste to be introduced into a new value chain without affecting the goal, since it may constitute a stage of the tuna life cycle.

2.2 | Data acquisition and life cycle inventory

Life cycle inventory (LCI) involves the compilation of inputs and outputs of the system (Tables 1 and 2; additional tables S.2, S.3. in Supporting Information S1). Primary data—number, age and dimensions of boats, fishing gears, homeports—were obtained from the Ministry of Rural Environment, Fisheries, and Food of the Government of Cantabria, as well as from a cluster of fishermen working in this community. A total of 17 fishing ships

TABLE 1 LCI of the fishing and transport (port to factory) stages. Data provided per reference flow of 1 kg of tuna landed in the Cantabrian sea

Vessel construction—Inputs from technosphere			
Material	**Unit**	**Construction**	**Maintenance**
Steel (hull)	g	1.38	8.28×10^{-2}
Iron (engine)	g	3.74×10^{-2}	1.31×10^{-3}
Chrome plating steel (engine)	g	9.78×10^{-3}	6.89×10^{-4}
Alloy (engine)	g	5.75×10^{-4}	2.02×10^{-5}
Paint	L	9.57×10^{-6}	9.57×10^{-6}
Antifouling	L	1.87×10^{-5}	1.87×10^{-5}
Nylon (seine net)	g	4.70	2.08
Ethylene vinyl acetate (seine net)	g	0.59	0.26
Lead (seine net)	g	2.05	0.11
Polysteel (seine net)	g	0.18	0.08

Fishing—Inputs from technosphere					
Material	**Unit**	**Value**	**Material**	**Unit**	**Value**
Diesel	L	4.80×10^{-2}	Ice	g	48
Lubricant oil	L	2.80×10^{-4}			
Fishing—Emissions to the environment					
Emission	**Unit**	**Value**	**Emission**	**Unit**	**Value**
CO_2	g	135.90	Cd	g	4.29×10^{-6}
CH_4	g	1.28×10^{-2}	Hg	g	1.28×10^{-6}
N_2O	g	3.66×10^{-3}	As	g	1.71×10^{-6}
SO_2	g	1.28	Cr	g	2.14×10^{-6}
NO_X	g	3.36	Cu	g	8.58×10^{-6}
CO	g	0.31	Ni	g	4.29×10^{-5}
NMVOC	g	0.12	Se	g	4.29×10^{-7}
SO_X	g	0.85	Zn	g	5.14×10^{-5}
TSP	g	6.44×10^{-2}	PCB	g	1.63×10^{-9}
PM_{10}	g	6.43×10^{-2}	PCDD/F	g	5.57×10^{-12}
$PM_{2.5}$	g	6.00×10^{-2}	HCB	g	2.17×10^{-8}
Pb	g	5.57×10^{-6}			
Transport (port to factory)—Inputs from technosphere					
Material	**Unit**	**Value**			
Fresh tuna	t·km	0.13			

(Figure 2) distributed in ports of four locations (Castro Urdiales, Colindres, Santoña, and San Vicente) participated in the study. It represents 50% of the total Cantabrian purse seine vessels with the albacore as target species. All the fishermen reported data linked to their fishing activities by means of a questionnaire, comprising both information regarding main capital goods (vessel dimensions and materials, useful lifetime, etc.) and operational aspects (amount and material of nets, consumption of diesel, ice, paint for maintenance, working hours, crew size, etc.). The comparison between the information from the Ministry and the fishermen made it possible to guarantee the reliability of the information and to complete a robust LCI. Data for the transformation of tuna into final can product were collected from a processing plant, also useful for the packaging waste treatment stage. This information includes energy, that is, electricity for machinery, and material inputs, embracing sunflower oil, which is the other main ingredient of the final product, fuel, or packaging, of each unitary process of the factory, as well as the output of fish waste generated through the production line. On the other hand, secondary data, that is, background processes, were added from the Ecoinvent v3.5 database (Wernet et al., 2016). In this regard, market process (unknown suppliers) were used and none of them were modified. Processes were selected according to the geographical location closest to Spain and their availability in the database: Spain, Europe, Europe without Switzerland, and global.

TABLE 2 LCI of the processing, transport (factory to stores and household to waste management site) and consumption stages. Data provided per FU (105 g can with 75 g of Bonito del Norte)

Processing—Inputs from technosphere					
Material	**Unit**	**Value**	**Material**	**Unit**	**Value**
Fresh tuna	g	203	Brine	L	5.00×10^{-2}
Electricity	kWh	3.50×10^{-4}	Aluminum can	g	15.6
Diesel	L	0.01	Aluminum folding	g	7.90
Water	L	6.56×10^{-1}	Cardboard box	g	9.58
Sunflower oil	L	0.12			
Processing—Outputs to technosphere					
Product	**Unit**	**Value**	**Waste to treatment**	**Unit**	**Value**
Bonito del Norte can	Units	1	Organic fish waste	g	8.53
Transport (factory to stores)—Inputs from technosphere					
Material	**Unit**	**Value**			
Bonito del Norte cans	t·km	3.71×10^{-2}			
Consumption—Outputs to technosphere					
Waste to treatment	**Unit**	**Value**	**Waste to treatment**	**Unit**	**Value**
Aluminum	g	1.56	Cardboard	g	0.79
Transport (household to EoL)—Inputs from technosphere					
Waste to treatment	**Unit**	**Value**			
Packaging waste	t·km	1.16×10^{-2}			
Organic waste valorization—Inputs from technosphere					
Material	**Unit**	**Value**	**Material**	**Unit**	**Value**
Organic fish waste	g	8.53	Antioxidant	g	3.31×10^{-3}
Bactericide	g	3.95×10^{-3}	Polypropylene	g	1.28×10^{-3}
Water	L	$1.02 \cdot 10^{-2}$	Energy	kWh	8.1×10^{-4}
Organic waste valorization—Outputs to technosphere					
Product	**Unit**	**Value**	**Product**	**Unit**	**Value**
Fish oil	g	0.49	Fishmeal	g	2.34

2.2.1 | Assumptions and limitations

The lifetime of the ships was assumed 30 years with annual maintenance operations, and 12% of the hull replacement every 2 years (Freón et al., 2014). The circular footprint formula (CFF) was applied for its manufacturing, considering both virgin and secondary steel. This formula defines the rule to allocate the environmental burdens or benefits of recycling, reusing, or recovering energy between, for example, the supplier and the user of recycled materials (European Commission, 2018). The CCF is used to model the EoL of a product as well as the recycled content, and is a combination of "material + energy + disposal," as presented Eq. (1), Eq. (2), and Eq. (3), reported in Supporting Information S1. The same formula was used for the packaging material. The principal engine is composed of 65% cast iron, 34% chrome steel, and 1% white metal alloys (Fréon et al., 2014) and is changed once during the vessel lifetime. The average life span of seine nets is about 5 years, although 25% are usually renovated every year due to losses at sea (Vázquez-Rowe, 2012). Their material composition is distributed in nylon for the net, ethylene-vinyl acetate (EVA) for the floats, lead for the ballast and polyester resin and polyethylene for the ropes and cables, according to the seine production described in Agribalyse database (Asselin-Balençon et al., 2020). On the other hand, paint for the vessel construction was considered one third of the amount of antifouling, as an approximation of the values ratio reported by Vázquez-Rowe et al. (2011), and the quantity of these materials for the maintenance is at least the same as that used the first time.

In relation to the fishing activity, none of the fishermen interviewed reported to produce their own ice or have an ice-making machine on board. Instead, they get the ice from the fishermen's associations. An energy consumption of 630 MJ/tonne was assumed for its production, based on a Galician port authority as reference. Also related to this storage and conservation, a limitation of the study lies in the lack of consideration of cooling agents from refrigeration chambers. Although emissions linked to refrigerants may entail important environmental impacts in terms of global warming and ozone layer depletion potential (Vázquez-Rowe et al., 2010), the data necessary to include this resource and emissions in the

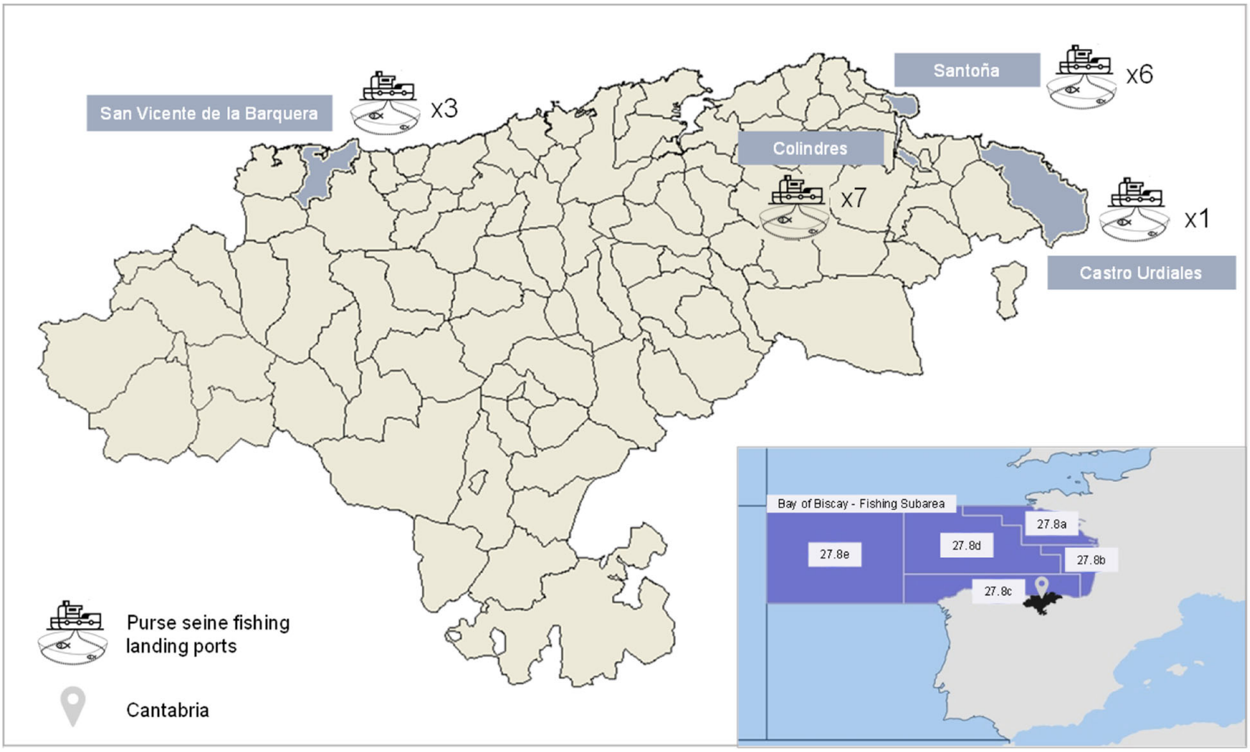

FIGURE 2 Location of the 17 purse seiners participating in the study by landing ports in Cantabria

modeling are not available, since the fishermen did not report any information in this regard. Furthermore, it is important to note that reliable data on refrigerant leakage is not available from official institutions at the Spanish level, so making assumptions could lead to greater uncertainty and poorer data quality.

The packaging waste management was based on the CFF previously described. According to the Final Product Environmental Footprint Category Rules for packaging, 60% of the aluminum for food cans and 75% of the cardboard packaging are recycled. The 86% of the non-recycled material goes to the landfill and the remaining 14% is incinerated (European Commission, 2021). On the other hand, the valorization processes of inedible by-products, as well as the inventory data for their modeling, were compiled and adapted from Cortés et al. (2021).

Finally, neither wastewater nor organic solid waste from the daily activity of the crew on board was considered in this study due to the lower contribution to the impacts shown in other studies (Vázquez-Rowe et al., 2010). Regarding the un-monitored emissions, the impacts resulting from the combustion of diesel in the engines were calculated on base of two references. Emission factors (EF) for CO_2, CH_4, and N_2O were based on the IPCC database (IPCC, 2006), whereas EF for SO_2 and other emissions, including particulate matter, NO_x or heavy metals were collected from the EMEP-Corinair Emission Inventory Handbook of 2006 (EEA, 2006). Likewise, EF for the use of the lubricant oil was obtained from the IPCC (IPCC, 2006).

Regarding the transportation among stages several inputs were taken. First, from the four fishing ports to the processing in Santoña (136 km of lineal route), considering that all landed tuna (3.062 kg) arrived to the canning industry. Second, from the factory exit gate to the points of sale distributed throughout the autonomous community of Cantabria in a circular route (495 km) with stops to unload the cans (3483 kg) in nine main towns selected. Third, 499 kg of the primary and secondary packaging from the households to the waste management in Meruelo, estimating the inverse circular route assigned for the sale distribution (495 km).

2.3 | Life cycle impact assessment

The software used was GaBi 9.2. (Sphera, 2019). The selection of the LCIA method and impact categories was based on those that provide a global view of the environmental sustainability of the product, addressing the damage caused by different phenomena and to different compartments. In addition, these indicators are those frequently used in LCA studies addressing fisheries and seafood products, according to the review of Ruiz-Salmón et al. (2021). The CML baseline 2001 method (Guinée et al., 2002) was considered as it is applied in around 50% of the articles, which makes the results easily comparable with other species or systems. Likewise, seven impact categories were evaluated in more than 40% of LCA-related studies. Among them, two toxicity-related indicators were considered, both expressed in kg of DCB (1,4-dichlorobenzene) eq.: terrestrial ecotoxicity potential (TETP) and marine aquatic ecotoxicity potential (MAETP) (Dincer & Bicer, 2018). Scarcity of resources is measured by the

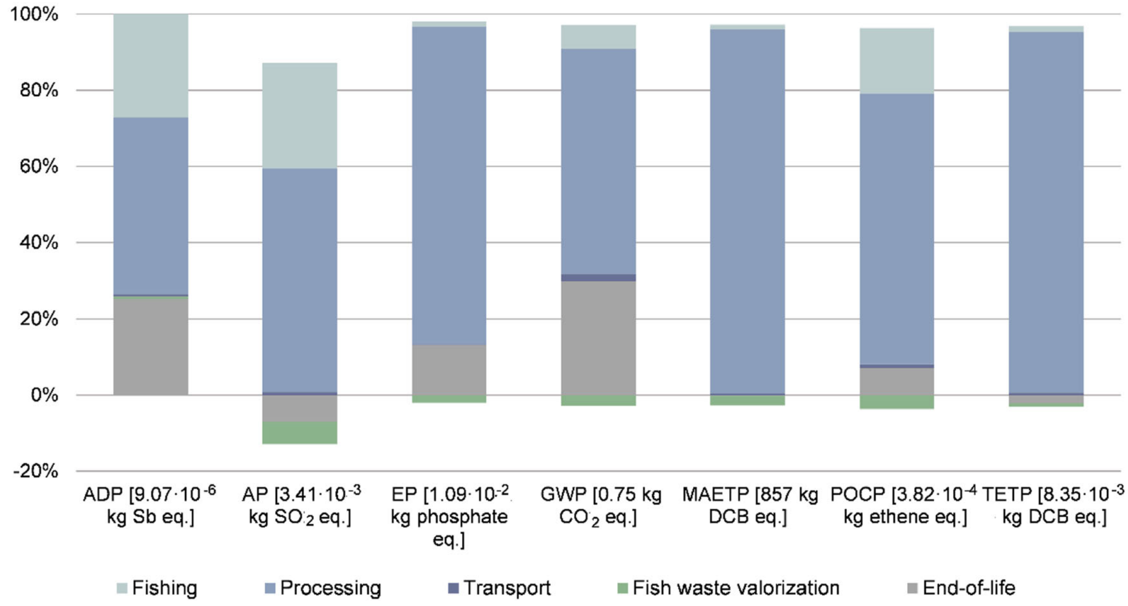

FIGURE 3 Total impacts and relative contribution of each life cycle stage to the global environmental burdens. The underlying data for this figure can be found in Supporting Information S2.

abiotic depletion potential (ADP), expressed in kg of Sb eq. (van Oers et al., 2020). Regarding categories addressing emissions to air and their impacts, photochemical ozone creation potential (POCP), measured in kg of ethene eq., (Jenkin et al., 2017), and global warming potential (GWP), calculated in kg of CO_2 eq., were assessed (Sultan et al., 2021). Finally, acidification potential (AP), expressed in kg of SO_2 eq. (Dincer & Bicer, 2018), and eutrophication potential (EP), measured in kg of phosphate eq., were considered to estimate the acid deposition of contaminants and the increase in aquatic plant growth due to nutrients, respectively (Cucek et al., 2015).

3 | RESULTS AND DISCUSSION

3.1 | Environmental performance of tuna supply chain

Figure 3 depicts the relative contribution to environmental impacts associated with the canned product, as well as the total burdens achieved in each indicator. Results revealed an MAETP impact of 857 kg DCB eq./FU, which was significantly higher than the toxicity value reported for terrestrial ecosystems, which makes sense since seafood supply chain negatively affect marine aquatic species, especially at the fishing stage. The carbon footprint (CF) accounted for 0.75 kg CO_2 eq. per FU. This impact, equivalent to 7.14 kg CO_2 eq./kg of processed tuna, was slightly lower than that estimated by Cortés et al. (2021), of 8.2 kg CO_2 eq./kg, who also identified the fishing and processing operations as the main contributors to GHG emissions. On the other hand, the remaining indicators ranged from about 10^{-2} (EP) to 10^{-6} (ADP). The main carriers of environmental degradation were the fishing and processing stages, with a combined contribution accounting for a maximum hardly higher than 100% (due to the avoided burdens of the waste management and valorization), and a minimum of 69.76% reported in GWP 100 years. Processing reported the major environmental impacts, averaging 79.18%. Regarding the fishing phase, its relative contribution was quite variable, with an average of 13.42%, and ranging from 1.30% (MAETP) to 37.23% (AP). With a lesser importance, although not negligible, was the EoL, spanning from −9.49% (AP) to 31.60% (GWP). It is worth nothing the negative percentages in AP, MAETP, and TETP from the recycling of aluminum and cardboard that avoids the manufacturing of virgin aluminum and cardboard products. On the other hand, fish waste valorization and transport phases showed minimal impacts in all indicators. In relation to the production of fishmeal and fish oil, all categories showed negative contributions to the total, up to −8%, with the exception of the ADP category, with a very low positive percentage (0.62%). Finally, the impact associated with transport was fairly constant, remaining below 2%, with the maximum achieved for GWP (1.89%). With the aim of analyzing the sources of degradation of each life cycle stage, all impacts are detailed in the upcoming sections (Sections 3.2–3.6).

3.2 | Fishing

The extraction of fish represented the second most contaminant stage in the supply chain, with important contributions in ADP, AP, and POCP. The production and use of diesel and net manufacture and maintenance had the worst environmental profile, as shown in Figure 4. Nets were responsible for the 99.0% of the ADP impact category, due to the use of scarce resources, such as the lead, and others related to fossil energies

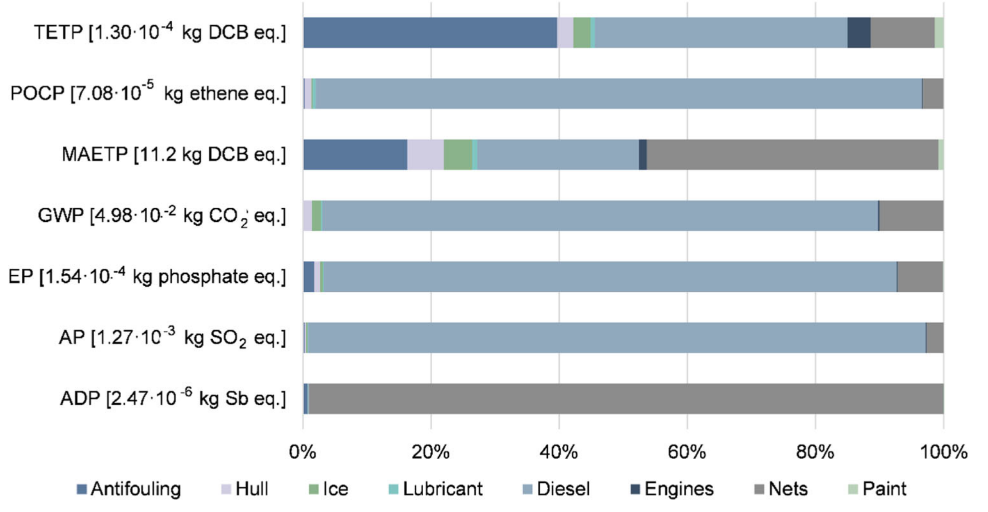

FIGURE 4 Total impacts and relative contribution of each resource to the global environmental burdens of the fishing stage. The underlying data for this figure can be found in Supporting Information S2.

(EVA, polyester resin or polyethylene) (van Oers et al., 2020). Nets also had the higher influence on MAETP (45.5%) and, on a lesser extent, on other impacts categories such as TETP (10.0%) and 9.98% in GWP. AP, POCP, EP, and GWP shared the diesel production and use by the fishing fleet as the main contributor with 96.4%, 94.6%, 89.4%, and 86.7%, respectively. Previous researches on purse seiners found that diesel consumption was the most relevant issue in terms of environmental burdens (Fréon et al., 2014; Vázquez-Rowe et al., 2010). In this work, focused on fisheries not far from the coastline, it was observed a fuel use intensity (FUI) of 48 L per tonne of landed tuna, following the decreasing trend over the last decades and one order of magnitude lower than purse seine consumption in the Atlantic, Indian or Pacific oceans, where distances to biomass stocks are larger. Besides, Parker et al. (2015) concluded that tuna catching by seiners is the largest fuel consuming among several species, but generally well performing compared to other fishing gears. They shared FUI ranging from 301–342 L/tonne for albacore, 439—471 L/tonne for bigeye, 349—459 L/tonne for skipjack, and 362—442 for yellowfin. Nevertheless, results from this work are comparable with the 21 L/tonne of Atlantic herring purse seining (Driscoll & Tyedmers, 2010) or the around 80 L/tonne of mackerel (Thrane, 2004). In view of the fact that the impacts obtained in the fishing stage are significantly lower than those reported by other studies that consider purse seine fishing, an uncertainty analysis has been developed using Monte Carlo simulation for all indicators, in order to obtain the representativeness of the results. This assessment is included and explained in Supporting Information S1. To complete the items involved in the use phase of the fisheries, lubricant for engines and ice for fish preserving were considered. Its impacts focused on the ecotoxicity categories and CF, with non-negligible burdens for the ice in MAETP (4.45%) and TETP (2.74%).

Regarding the activities related to the vessel construction, their impacts were mainly associated with MAETP, TETP, and GWP. For instance, antifouling was the biggest contributor to ecotoxicity categories, previously observed in tuna's fisheries (Hospido & Tyedmers, 2005). Concretely, it was the largest issue in the TETP (39.7%), the third in MAETP (16.3%) and slightly affects AP and ADP. Paint also contributed to the latter categories with less than 2%. The steel for manufacturing the hull was responsible for 5.61%, 2.44%, and 1.35% of the impact in MAETP, TETP, and GWP, respectively, and the engines also influenced MAETP and TETP with 1.24% and 3.58%, respectively.

This extractive tuna fishing is an activity that generates an important sensitivity among both stakeholders and consumers, with sustainability being the most important aspect to be guaranteed, which is promoted and supported by the application of LCA. There are different certifications that accredit and inform in a clear, rigorous, and contrasted way that fishing activities are developed in a sustainable and responsible way. The AENOR responsible Fishing Tuna Certificate (APR) based on the UNE 195006 standard has become a powerful tool ensuring that five basic pillars are contemplated in tuna vessels: working conditions, control of fishing activity, maritime control, sanitary control, and good fishing practices (AENOR, 2016). Likewise, another certification is the Marine Stewardship Council (MSC) seal, which informs that species are sustainably captured according to the good practices recommended by official organizations, scientists, governments, and the fishing industry (MSC, 2022).

3.3 | Processing

Environmental impacts illustrated in Figure 5 reveal the main sources of pollution and degradation along the processing of fresh tuna into fish cans. The critical categories identified in Section 3.1. GWP and MAETP presented important contributions of the processing stage. GHG emissions generated 0.47 kg CO_2 eq./FU, whereas the impact on MAETP reached 866 kg DCB eq., constituting about 96% of the total. It is also interesting to highlight the values achieved in TETP (8.45×10^{-3} kg DCB eq.) and EP (9.45×10^{-3} kg phosphate eq.), which represented 82.71% and 95.24% of the total, respectively (see Figure 3).

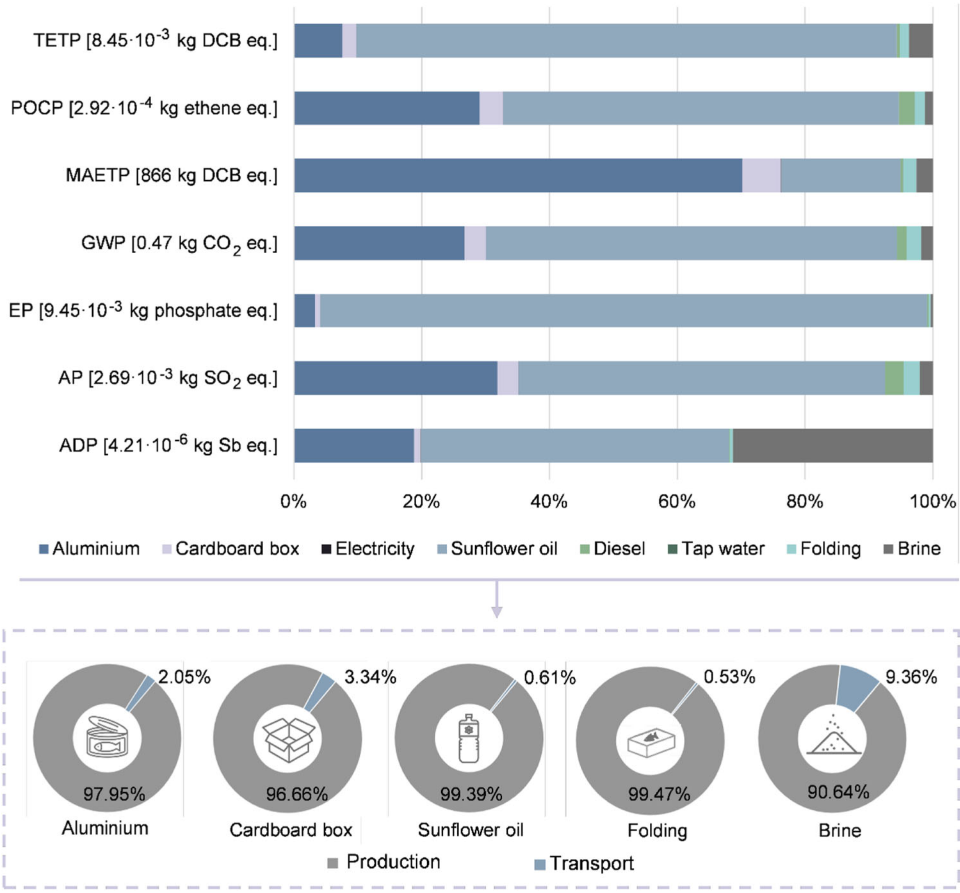

FIGURE 5 At the top, total impacts and relative contribution of each resource to the global environmental burdens of the processing. At the bottom, average contribution of the production process itself and transport to the impact associated with each resource. The underlying data for this figure can be found in Supporting Information S2.

The use of sunflower oil achieved the largest contribution to any impact category (excluding MAETP), ranging from 48.25% (ADP) to 94.95% (EP). In this indicator (MAETP), aluminum cans presented the main load carrier on the marine ecosystems (70.17%), with contributions near to one fourth of the impact in other categories, such as POCP (29.08%), GWP (26.68%), and AP (31.84%). Similar trends were reported by Almeida et al. (2015), who analyzed canned sardine; Laso et al. (2017), evaluating canned anchovy; and Cortés et al. (2021), Avadí et al. (2015), and Hospido et al. (2006), who developed the LCA of tuna cans. These authors identified the provision of aluminum or tinplate cans as one of the chief hotspots of the systems. Likewise, Iribarren et al. (2010) recognized oil production as an important contributor to impacts for canned mussel, especially in EP (85.4%), GWP (31.6%), and POCP (41.6%). On the other hand, brine production (including transport), is only relevant in ADP elements (31.31%) due to the consumption of resources, while in the other indicators, it hardly exceeded 4%. The remaining resources presented relative constant and low contributions: cardboard affected between 0.81% and 6.04%, folding from 0.33% to 2.48%, and electricity, diesel, and tap water averaged 0.02%, 0.03%, and 0.03%, respectively. Finally, it is worth noting that, on average, the resources production processes themselves controlled practically all the impact (90.64—99.47%), whereas the transportation considered in the supply chain of these materials achieved quite low percentages, with that of brine as the most relevant (9.36%).

3.4 | Fish waste valorization

Unlike other seafood LCA-related articles, this study considered the valorization of the main by-products that are not suitable for human consumption, that is, fish heads, viscera, bones, and other organic waste, in addition to environmental credits. Negative impacts were achieved in all categories, except ADP, which translates into an environmental benefit associated with the lack of production of new products, in this case, fishmeal and fish oil, which had an average negative contribution of 90%. The use of electricity in the fishmeal plant, and, to a lesser extent, the consumption of antioxidant, polypropylene, tap water, and bactericide, presented positive impacts and relatively constant contributions in the seven categories, always remaining below 10%. Regarding ADP, nearly 90% of the total positive impact was attributed to the application of antioxidant; nevertheless, this load can be considered negligible in terms of the overall system, accounting for 0.33% (see Figure 3).

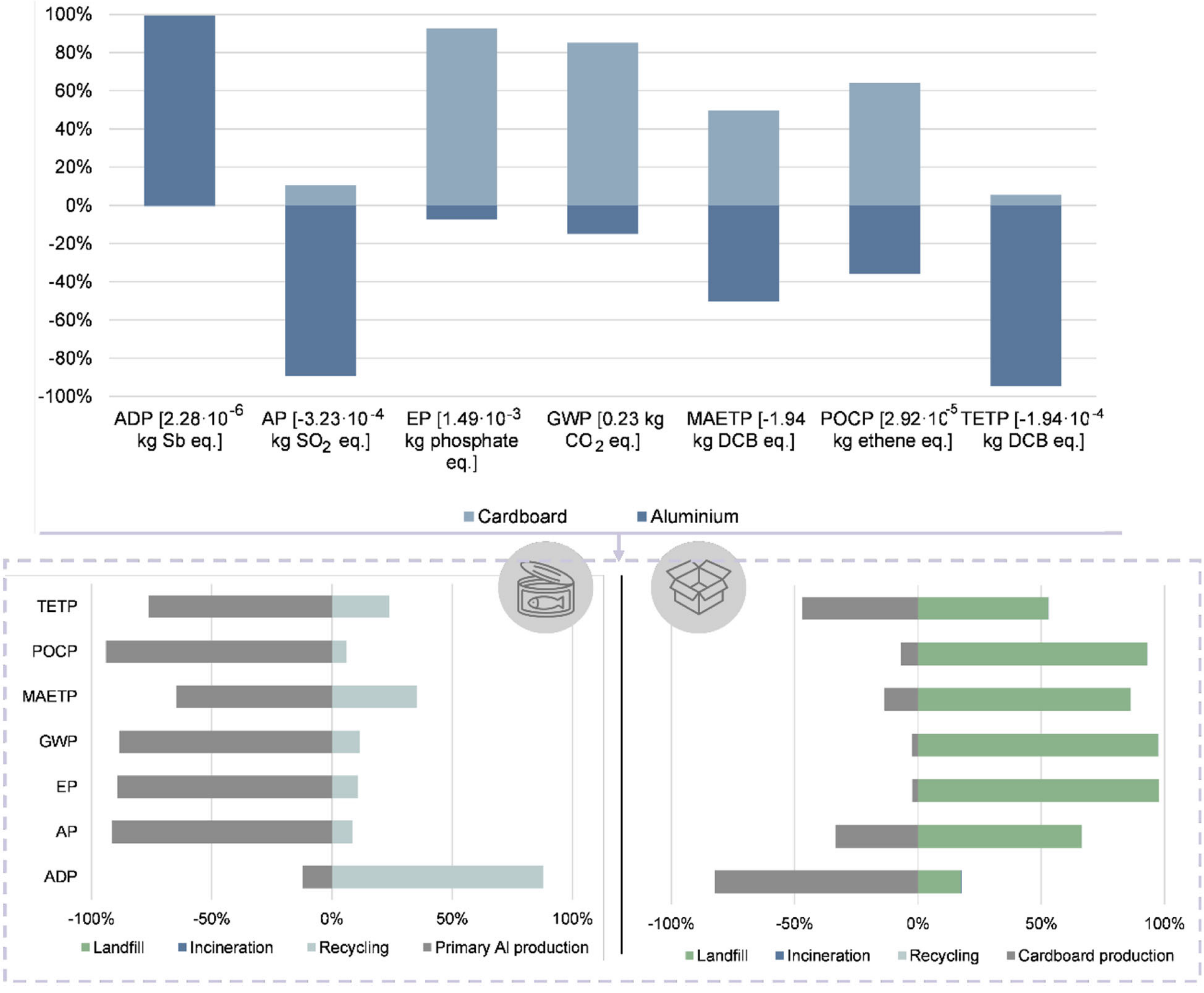

FIGURE 6 At the top, total impacts and relative contribution of each packaging management to the global environmental burdens. At the bottom, contribution to the impact of each waste management treatment for aluminum (left) and cardboard (right). The underlying data for this figure can be found in Supporting Information S2.

3.5 | Packaging end-of-life

Figure 6 depicts the impacts (positive percentage) and environmental credits (negative percentage) for the cardboard and aluminum waste treatment. Results displayed avoided impacts in all categories for the aluminum, excepting ADP. The waste treatment, mainly due to the recycling process (negligible contribution of disposal and incineration), revealed saves of more than 80% and 90% for AP and TETP categories. The primary aluminum production, with an important use of resources and energy, is contrasted with the recycling efficiency to avoid burdens in the majority of indicators included. On the contrary, cardboard contributed the most to the impacts. The diagram at the right bottom of Figure 6 shows the burdens coming from the landfilling (negligible contribution of recycling and incineration), and they are imposed to the aluminum credits. Environmental impacts of the cardboard landfilling were due to its high content on elements such as sulfur and chlorine (Margallo, 2014) and CH_4, CO_2, and other leachate emissions (Villanueva & Wenzel, 2007). Thus, EP, GWP, and POCP were ruled by the cardboard treatment, and MAETP was balanced by the two materials.

3.6 | Transport

Few LCA publications about the fish sector included the transportation between stages. Farmery et al. (2015) reported the transport of lobster to the processing after fishing and Driscoll et al. (2015) included the distribution prawns to retail, together with the capture, processing, and storage.

Very low values (less than 1% of relative contribution, excepting GWP) compared to the fishing or processing were observed for transport. Results from Driscoll et al. (2015) showed an impact around 5—30% for the transport, while Farmery et al. (2015) reported less than 5% contribution due to higher distances and a greater number of stages considered. For tuna, light differences between each distribution appeared because of distances and tonnage variation and the major impacts are given by GWP, which represented the 1.50% of the total CO_2 emitted in the whole supply chain analyzed, always attributed to the fuel combustion. Nevertheless, although 80% of the processed fish comes from Cantabrian ports and the waste management plant is placed in the same region, limits to this estimation exist because the internationalization of this kind of gourmet product is growing. Indeed, the company currently exports its products to more than 10 countries but data of sales were not available. To approximate the implications of exportations may have, Farmery et al. (2015) obtained an impact 13 times higher when the prawn was distributed from Australia to Japan, instead of the national sales. Therefore, the environmental burdens estimated in this work are undervalued for the distribution.

4 | CHALLENGES, LIMITATIONS, AND PERSPECTIVES

One of the main problems faced was the uncertainty associated with the quality of the inventory data. Epistemic errors, that is, primary data gaps, tried to be overcome by making use of secondary data. These assumptions and hypotheses were supported by the current literature addressing the LCA of the target species, but also based on other fishing gears, which probably influences the impacts. In order to avoid more uncertainty, some aspects that could have relevance in the modeling and results, such as the consideration of cooling agents and leakage of refrigerants, were omitted. In addition, background processes from the Ecoinvent database are also prone to uncertainty since the systems are not specific to the conditions under study (Avadí & Freón, 2014).

Another frequent weakness of LCA studies occurs during the design and application of the methodology, when the LCA practitioner has alternative approaches from which to choose, leading to widely varied results. For instance, purse seine fleets capture simultaneously more than one species during fishing operations, so allocation is crucial for addressing this issue (Ruiz-Salmón et al., 2021). In this case, a mass allocation was considered the most appropriate since the species are obtained from the same process and inputs and outputs of the inventory data affect them in the same manner. However, an economic assignation considering the economic value of each species could be an interesting alternative, which probably lead to quite different results. Likewise, a system expansion of the system would be a more suitable option to avoid allocations, as the ISO 14040 standard recommends. Unfortunately, in this particular case, this is a complex task, which requires going into the life cycle of each fish product, taking us away from the objective.

Finally, the selection of environmental impact categories is essential for understanding the global performance of the system. The indicators chosen are considered adequate and allow a simple comparison with the impacts generated by other species, but the introduction of alternative categories, such as biotic resources depletion or seabed damage (Woods & Verones, 2019), or novel ones, like those linked to plastic pollution or marine litter, may be of particular interest in a context where marine environment degradation is a worsening problem (Boulay et al., 2021). Unfortunately, there are several challenges creating an impact assessment category for marine litter due to lack of data, so that it is still under the development a methodological standard to measure concentrations, dispersal, and composition of microplastics (Saling et al., 2020).This particular limitation opens the door to future research in the direction of expanding the system boundaries and using a greater number of impact categories that allow greater accuracy, which would help both to promote sustainability and to have a scientific basis for the possible search and definition of policy actions that positively impact the sector.

5 | CONCLUSIONS

This work developed a thorough environmental analysis of tuna cans involving the whole supply chain. The collection of primary inventory data based on fishing activities developed in this area, allowed the development of an LCA considering a realistic scenario that serves as basis for future seafood impact analysis. The outcomes of the study demonstrated that the processing stage was the main contributor to all environmental impacts, whereas fishing activities occupied the second place in AP, ADP, and POCP. The production and consumption of diesel in fleets was identified as a hotspot, a common issue with the majority of the food sector, as well as the use of sunflower oil and aluminum cans. Transport showed insubstantial environmental burdens in all categories, mainly driven by regional displacements and local consumption, which is recommended to continue promoting. Likewise, the evaluation of packaging waste management and valorization of fish waste only accounted for less than 10% of the credits, something far from real sustainability.

The advance of this study is based on the fact that the results can give new information in tuna capture by purse seine fishing, allowing the comparison with previous and future researches, and making it possible to identify the chief environmental pressures exerted by this sector, which facilitates the work of LCA practitioners when compiling inventory data. In this regard, limitations of the study, that is, inventory, allocations, or environmental categories selections, should be taken as a catalyst for future studies that cover these issues and broaden the approaches. In addition, although embracing the sustainable development goals seems a distant view that requires the commitment of all the agents involved, the inclusion of waste valorization strategies for the production of by-products goes a step toward the circular economy, applying cradle-to-cradle principles. To this end, it is essential to highlight the importance of tools such as LCA, which has been proven to be a key instrument in environmental analysis, and which could provide support and guidance to policy makers in terms of sustainability of the seafood sector.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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