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Abstract

The sustainable and continued production of enough food to feed the entire world´s population is one of the main concerns in the food industry. Spain, and in particular Galicia, which is an eminently fishing region characterised by the consumption of large quantities of fish, both fresh and processed, must face the challenge of shifting its seafood productive fabric towards a circular economy. To achieve this objective, the first task is to demonstrate that circular economy principles allow to reduce the environmental impacts associated with seafood production. In this sense, this study proposes the environmental evaluation of the skipjack tuna (*Katsuwonus pelamis*) value chain within a canning industry located in Galicia through the LCA methodology from an attributional perspective, including the valorisation processes for biowaste (edible and inedible by-products). Results indicate that the main crucial subsystems of the value chain are tuna fishing and the canning process, as it was expected considering other similar studies on seafood products. Moreover, this specific case study demonstrates that the multi-product strategy applied to the canning sector is environmentally viable. Thus, although the environmental impacts of the entire system are increased by including further valorisation operations, the environmental loads assigned to the main product (canned tuna) decrease compared to the one-product system by assigning environmental burdens to other value-added products (tuna pâté, fishmeal, and fish oil).

Keywords

Life Cycle Assessment; Canned tuna; Value chain; Valorisation; By-products

1. Introduction

As the world´s population has been expanded, the demand for food and energy has seen a rapid increase. In fact, all projections indicate that at least a 70% increase in food production will be needed to meet food demand by 2050 (FAO, 2012), which is expected based on increased yields and productivity of crops, livestock and fisheries. Food production is recognized as a major contributor to environmental impacts in both developed and developing countries (Nemecek et al., 2016), amounting to around 13.7 billion metric tons of CO_2 eq (Poore and Nemecek, 2018), which represent 26% of global anthropogenic greenhouse gas (GHG) emissions (Parker et al., 2018). Delving deeper into the key drivers of this high environmental impact, in addition to the intrinsic impacts of food production itself, other "avoidable" impacts play a major role, such as the environmental burdens related to food packaging and distribution worldwide (Yokokawa et al., 2018). In a global market, the consumption of some products presents a large impact when considering the entire production chain from a life-cycle perspective (cradle-to-plate approach).

In particular, focusing on the fisheries sector, the situation in the oceans is agonizing, with fish stocks being decimated over the years all over the world (Wilson et al., 2020). The state of the oceans is becoming extremely worrying over time. In 2017, the maximum peak of overfished marine stocks (34.2%) and a minimum of underfished stocks (6.2%) was reached, according to the results published in FAO (2020). In parallel to the increasing rise of overfishing, aquaculture continues to grow steadily, to the point that today fish produced in aquaculture facilities account for 46% of total fish production (FAO, 2020). At this point, an intense debate has started to emerge regarding the long-term sustainability of wild fisheries or whether aquaculture should be chosen as the main fish source (Ruiz-Salmón et al., 2021). The valorisation of waste and discard fractions for the production of fishmeal and fish oil to be used for the formulation of feed for farmed fish also needs to be considered (Fréon et al., 2014c). There is growing evidence that the approach to utilize such fractions: fish bones, viscera, heads and other less desirable parts as raw material for the production of value-added products such as omega-3 acids and collagen, although these alternatives are at a less developed stage for industrial implementation (Laso et al., 2018a).

In Spain, a country that has traditionally been an important fishing nation from the point of view of catching, processing and consumption (Vázquez-Rowe et al., 2014), 922,564 tons of fish and seafood were landed in 2018, making Spain the first country in the European Union, both in terms of volume and value, with almost 2,150 million euros (European Commission, 2020a). Spain has also developed an important seafood processing sector, especially smoked, processed and, above all, canned seafood. Domestic canned tuna production leads EU production, accounting for approximately 70% of the total volume (García-del-Hoyo et al., 2017). Specifically, the volume of canned seafood production by Spanish companies reached 353,000 tons in 2018, being Galicia (NW Spain) the leading region at national level, accounting for more than 85% of Spanish production (EUMOFA, 2019).

Galicia´s canning tradition means that it is home to 7 of the 10 largest companies on the Spanish canning sector, including the Top-5 (Ardán, 2018). Moreover, the presence of small and medium-sized enterprises (SMEs) is predominant in the Galician canning sector, with a high percentage of small companies (<50 employees), which represent 66% of the total, even highlighting that 22% of the total number of companies are very small with less than 10 employees (Ardán, 2018).

Numerous initiatives and projects for the development of circular economy strategies are already underway in different companies. However, due to the aforementioned characteristics of the Galician canning industry, it is difficult for these initiatives to permeate the market and in the present context the Galician canning sector must face the challenge of the current paradigm shift from a linear economy to a circular economy in which the main objective of companies must be to maximize production through the valorisation of waste (Ciccullo et al., 2021). In this sense, among the actions to be developed to achieve a complete integration of the circular economy within the canning sector, the following stand out: (i) the use of processing techniques with a low environmental impact; (ii) the reduction of the packaging residues; (iii) the valorisation of wastewater flows; and (iv) the accomplishment of the objective of zero biological waste, valorising all biowaste fractions to produce new value-added products. With this in mind, the canning industry in general, and the Galician canning industry in particular, has enormous room for improvement, since a large part of the fish is directly discarded (heads, viscera, bones, etc.), which can open the door to the development of new products (García-Santiago et al., 2020).

Circular economy emerges as an opposite solution to the current linear system as a sustainable system where economic growth is decoupled from resources use, through the reduction in the consumption and the recirculation of raw materials (Korhonen et al., 2018). On the main points of the circular economy is the reduction of waste generated throughout the value chain, valorising them as raw materials for the generation of added-value products. However, increasing circularity does not necessarily translate into a direct reduction of environmental impacts (Niero and Kalbar, 2019), which creates a dilemma for decision-makers when selecting adequate circular practices and innovations (Rufí-Salís et al., 2021). The impacts or benefits generated by these circular strategies are often measured through the use of circularity metrics (Corona et al., 2019). Life Cycle Assessment (LCA) methodology, as it is based on the quantification of the inputs and outputs of a system, becomes a good example of a circularity assessment tool to quantify and evaluate the benefits or impacts of circular economy strategies. The application of LCA methodology to determine the environmental impacts of fish catches, farming (aquaculture), and processing started in the mid-2000s. A long list of LCA seafood studies on diverse pelagic species such as horse mackerel (Vázquez-Rowe et al., 2010), Peruvian and Cantabrian anchovy (Fréon et al., 2014b; Laso et al., 2018b), carp (Hornborg and Främberg, 2020) or Atlantic mackerel (Ramos et al., 2011) have been reported. Demersal species such as hake (Avadí et al., 2018; Vázquez-Rowe et al., 2011b), cod (Svanes et al., 2011; Ziegler et al., 2013) or octopus (Vázquez-Rowe et al., 2012b), crustacean species such as prawns (Farmery et al., 2015; Medeiros et al., 2017), lobster (Driscoll et al., 2015) or goose barnacle (Vázquez-Rowe et al., 2013a), and bivalve species such as Atlantic scallop (Cortés et al., 2021) have been reported. Regarding aquaculture, different studies on mussels (Iribarren et al., 2010b, 2010c; Lourguioui et al., 2017; Tamburini et al., 2020), oysters (Tamburini et al., 2019), turbot (Iribarren et al., 2012) or salmon farming (Philis et al., 2021) can be highlighted. It is also important to mention that traditionally not only fishing or farming activities have been evaluated, but also the production of different fish- and seafood-based products such as fish sticks (Vázquez-Rowe et al., 2013b), fishmeal and fish oil (Fréon et al., 2017) and canned products (Almeida et al., 2015; Avadí et al., 2015, 2014; Iribarren et al., 2010a; Laso et al., 2017; Vázquez-Rowe et al., 2014). Review articles on fishing (Avadí and Fréon, 2013), aquaculture (Bohnes et al., 2019; Bohnes and Laurent, 2019; Philis et al., 2019) and processing (Ruiz-Salmón et al., 2021; Vázquez-Rowe et al., 2012a) stages have also been evaluated.

This study proposes the environmental evaluation of the skipjack tuna (*Katsuwonus pelamis*) value chain within a canning industry located in Galicia through the LCA methodology. The production line focuses on gourmet products, with high added value, basing its production on local raw materials, with traditional manufacturing methods and using, as far as possible, certified organic ingredients. Thus, the processing plant meets some of the circular economy principles: (i) the fish is caught with traditional techniques in national fishing grounds; (ii) traditional techniques such as cooking in seawater and air-drying are followed; (iii) the primary packaging is made of aluminium, so it is 100% recyclable; (iv) high quality by-products (non-canned edible parts) are used to produce other products; (v) the low-quality by-products are valorised in the form of fishmeal that could be used for animal feed. In this way, the canning plant minimises the consumption of raw materials, minimises transport and follows a multi-product strategy. The main objectives of the study are to determine the environmental viability of this approach and to lay the foundations for the way forward for other companies to position themselves in a highly competitive market. The main novelty of this study lies in the fact that the LCA methodology has been used to analyse the environmental impacts of the entire canned tuna value chain, and not only those impacts assigned to the production of the main product. The inclusion of the valorisation processes of residual organic fractions within the system boundaries makes it possible to analyse the product from a broader point of view and opens the door to the identification and evaluation of opportunities for environmental improvement.

2. Materials and methods

2.1. Defining the goal and scope. Impact assessment methodology.

Moving towards a veritable circular economy requires taking small steps to demonstrate the viability of multi-product processes from an environmental point of view. In this sense, this study aims to assess the environmental sustainability of the entire canned tuna value chain following the Life Cycle Assessment methodology (ISO 14040; 14044) from a attributional perspective. Although the main product is canned tuna, all stages of the value chain were included within the system boundaries, including the manufacture of by-products and the valorisation of organic waste. Thus, the main objective of this study is to determine from an environmental point of view whether the production of multiple value-added products is more sustainable than single-product approaches.

A cradle-to-gate approach was considered in the study, that is, considering the extraction of raw materials to produce the required inputs and the manufacture of the products, but not the consumption and final disposal stages. This perspective was assumed since the main objective of the study is to recognize the environmental implications of the production of tuna-based products. The main raw material is skipjack tuna, so fishing and transport to the canning plant, as well as the production and transport of other ingredients and packaging materials, were included in the system boundaries. The Functional Unit (FU) considered for assessment was 1 tonne of raw tuna at processing plant gate since it seems consistent to select a feedstock-based FU as the plant is characterized by its multi-product nature. The software SimaPro 9.0 (PRe-Consultants, 2017) was used for the computational implementation of the inventories. The life cycle impact assessment step was carried out using the ReCiPe 2016 v1.1 methodology in a hierarchist perspective at midpoint level (Huijbregts et al., 2017). The environmental burdens were calculated in terms of the following impact categories: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Mineral Resources Scarcity (MRS) and Fossil Resources Scarcity (FRS).

2.2. Description of the system under study.

The value chain associated with canned tuna was divided in 4 different subsystems, as depicted in Figure 1. Subsystem 1 is related to the fishing and transportation of tuna as the main raw material to supply the canning plant. Subsystems 2-4 are linked to the different activities and operations that take place within the canning factory. It is important to note that the aim is to use the residual fractions of the process to produce value-added products; however, the treatment of non-recoverable waste and wastewater has been included in all subsystems. All liquid fractions are directly sent to a municipal wastewater treatment plant located close to the site. On the other hand, packaging waste is recycled as far as possible and landfilled or incinerated according to the Spanish profile.

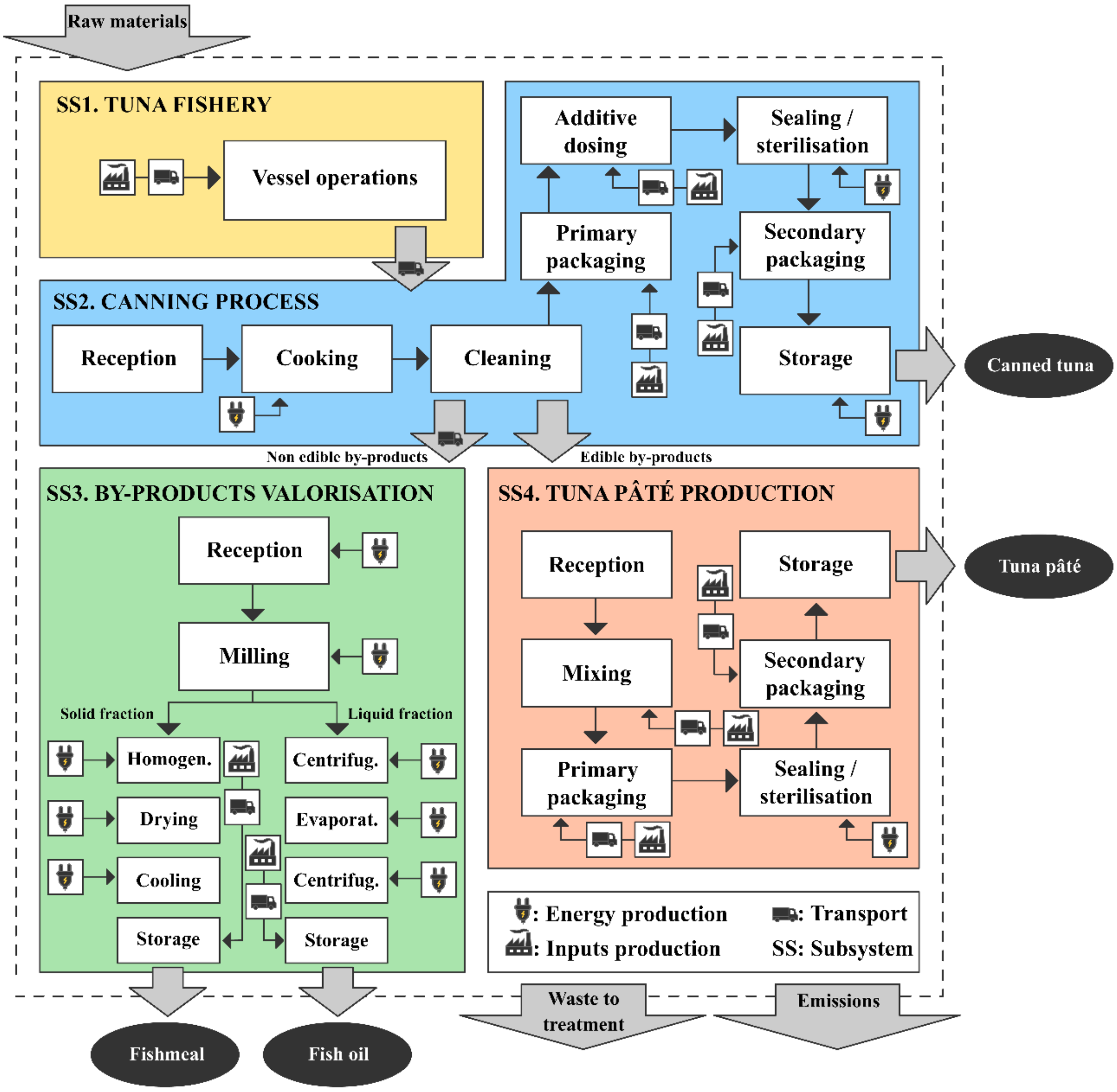

Figure 1. System boundaries for the environmental assessment of canned tuna value chain.

2.2.1. Tuna fishery (SS1)

This subsystem includes all operations related to tuna fishery in FAO 34 waters. Tuna fishing is carried out by small vessels belonging to local coastal communities, using traditional and highly selective methods. Thus, the pole-and-line method is used, a method recommended by organizations and research to limit catches, avoid overfishing and minimize discards (Khan et al., 2018). Sardine (*Sardina pilchardus*) is used as bait in this fishery, so sardine fishing by an average purse seine fleet, which is landed in port and processed for bait production was included within the system boundaries of this subsystem as detailed in Vázquez-Rowe et al. (2011). Tuna, once caught, is discharged in the port of Arrecife (Lanzarote-Canary Islands) and transferred by ship to the port of Algeciras (Cadiz-Andalusia), and then transported by road to the canning plant located in Galicia.

2.2.2. Canning process (SS2)

This subsystem includes all the operations carried out in the canning plant that are directly related to the main product (canned tuna), from the extraction and production of the raw materials and fuels and the transport of these from their place of origin to the processing plant. This subsystem is composed by the different operations that are performed in the canning plant: the tuna pieces are unloaded and stored in a cooling chamber at reception until they are transported to the processing stage. The rest of the products and ingredients are stored in conventional areas until they are needed. The tuna is then cooked whole and not defrosted. Once cooked, the tuna is cooled in the plant overnight. The next morning, the tuna is cleaned, and the loins are obtained for canning and other by-products for use in other production lines or for valorisation. In this step, it is important to note that for every 1,000 kg of tuna that enters the plant, only 365 kg are canned.

The other parts are sent to valorisation processes, 8 kg of edible by-products are sent to tuna pâté production, while the remaining 627 kg of inedible by-products are used for the production of fishmeal and fish oil. Every 18 g can is filled with 90 g of tuna loins and 30 g of an additive composed of water, salt, and some vegetables. Once filled, the cans are closed, sealed and sterilised in an autoclave, leaving them completely watertight and disinfected. Finally, cans are placed in individual cardboard cases for sale. 10 cases are shrink-wrapped with plastic film and 5 of these packages are placed in cardboard boxes which are stored until their distribution and marketing.

2.2.3. Production of tuna pâté (SS3)

By-products tailored for human consumption that are not used for canning (e.g., gut meat or near the tail) are used to produce a tuna and black olive pâté that is marketed by the company. This pâté is composed of tuna (52%), olives (22%), extra virgin olive oil (12%), mashed potatoes (9%) and other minority components such as onion, garlic, black pepper and salt (5%). Once the parts of the tuna to be used for this pâté have been separated, they are directly crushed and mixed with the rest of the components of the pâté since tuna is already cooked. 125 g of the mixture is dosed into a 146 g glass jar, covered with an aluminium lid (8 g) and placed in a steriliser. A 0.5 g adhesive label is then added, and 10 jars are placed in cardboard boxes for storage and distribution.

2.2.4. By-products valorisation (SS4)

The by-products that are not suitable for human consumption (heads, viscera, bones…) are taken to the crushers, where their size is reduced to less than 50 mm, and then to the storage hoppers. Pressing produces a press cake (solid phase) and water and cooking oils (liquid phase). The press cake passes through a homogeniser before being sent to the drying process which is carried out continuously inside the dryers to remove excess water at a temperature of around 100ºC. To continue the process, the temperature of the fishmeal is cooled by means of a sleeve cooler. Subsequently, the fishmeal is subjected to a grinding process in order to obtain a homogeneous product. Finally, the fishmeal is stored in silos, where it is shipped both in bulk and packaged in 25 kg format.

Conversely, with the help of a tricanter, the liquid phase is introduced into a continuous centrifuge, where the liquid is separated from the remaining solids, which are incorporated into the press cake before entering the dryer. At the outlet of the tricanter, the cooking water is concentrated by means of a double effect evaporator, using the exhaust gases from the press cake dehydration. Fish oil undergoes another centrifugation process to remove impurities and humidity before being stored in tanks until it is shipped.

2.3. Life cycle inventory data collection and allocation approach

Data acquisition for the life cycle inventory (LCI) was mainly obtained through primary sources, provided by the canning company. A questionnaire was filled in by the company's staff, which collected all information related to the material and energy consumption of the plant. Data related to tuna fishing and transport (SS1) were obtained from the supplying company, which operates in the port of Arrecife. Details of material consumption were established following key parameters previously established as relevant in previous studies of fisheries for different species (Ramos et al., 2011; Vázquez-Rowe et al., 2011b, 2011a). Primary data on the bait requirements of the fleet were also obtained. In this regard, the sardine (*Sardina pilchardus*) fishery by an average purse seine fleet, which is landed in port and processed for bait production, was included within the system boundaries of this subsystem, as detailed in Vázquez-Rowe et al. (2011).

SS2 and SS3 data were obtained directly from a comprehensive questionnaire completed by cannery workers. This questionnaire detailed both the material and energy consumption of the plant, as well as a description of all the processes carried out in the canning plant. The production of the aluminium can considered the virgin/recycled aluminium ratio as 63/37% (Laso et al., 2017). Although the life cycle inventories of the production of the agricultural ingredients were taken from Ecoinvent, the production of Extra Virgin Olive Oil (EVOO) was taken from Laso et al. (2017). The transport of materials was taken into account considering primary information on the place of origin of the different raw materials. By-product valorisation data (SS4) was based on information from the environmental declarations of one of the most important plants belonging to leading Spanish companies in the fishmeal sector. The total production capacity of the plant is 50,000 tonnes/year for an average production of about 14,000 tonnes/year of fishmeal. Thus, primary data related to the generation of fish by-products were used to associate this production line with the rest of the data in the study. Is important to note that the life cycle impacts related to the production of the background processes (embodied emissions from raw material production processes) were taken from the Ecoinvent v3.5 database (Moreno Ruiz et al., 2018), considering the information obtained from primary sources.

With all this primary information and some secondary data sources, the life cycle inventory was compiled, which involves the collection and computation of specific data that allow quantifying those inputs and outputs in the production system that contribute to a given impact category (Vázquez-Rowe et al., 2013b). **Table 1** contains the complete life cycle inventory of SS2, as it could be considered the core of this study; however, the detailed life cycle inventories of each subsystem considered in the study are shown in Tables S.1, S.2 and S.3 of the supplementary material.

Table 1. Life cycle inventory of the Subsystem 2. Canning process per FU (1 tonne of raw tuna at processing plant).

SUBSYSTEM 2. CANNING PROCESS					
Inputs from the Technosphere					
Materials	**Unit**	**Value**	**Transport**	**Unit**	**Value**
Tuna from SS1	kg	1,000	Tuna	t·km	2,097
Powder onion	g	241.2	Powder onion	kg·km	282.2
Powder garlic	g	160.8	Powder garlic	kg·km	188.1
White pepper	g	80.4	White pepper	kg·km	94.1
Salt	g	602.9	Salt	kg·km	30.1
Aluminium can	kg	73	Aluminium can	t·km	1.2
Bleached board	kg	36.5	Bleached board	t·km	27.0
Plastic film (LDPE)	kg	3.2	Plastic film	kg·km	255.1
Corrugated board	kg	34.5	Corrugated board	kg·km	621.9
Water	L	120.6	Cardboard waste	t·km	2.7
Sea water	L	5,096	Plastic waste	kg·km	347.8
Energy	**Unit**	**Value**			
Electricity	kWh	180.8			
Natural gas	MWh	2.6			
Outputs to the Technosphere					
Products	**Unit**	**Value**	**Waste to treatment**	**Unit**	**Value**
Canned tuna	Amount	4,055	Biowaste	kg	17.3
Co-products	**Unit**	**Value**	Plastic to recycling	kg	2.8
Inedible by-products to SS3	kg	627	Cardboard to recycling	kg	21.5
Edible by-products to SS4	kg	8	Wastewater	m^3	16.2

The scenario under assessment is a multi-output system where more than one product is obtained. According to the functional unit chosen (1 tonne of tuna entering the canning industry), no allocation procedure was required. This system is a clear example of system expansion, following the guidelines set out in the ISO standards for dealing with multi-product systems. However, the use of allocation factors seems unavoidable to assess the environmental performance of a particular product; and even more so, within these circular processes, where the objective is precisely to maximise the production of outputs while minimising the consumption of inputs. In this case, although the main objective is to establish the environmental profile of the overall process, the economic values of all products have been taken into account, in order to be able to relativise the environmental burdens of the system in comparison with other food systems. **Table 2** includes the different market prices considered, as well as total amount of produced outputs. The total production and market prices of canned tuna and tuna pâté were calculated considering only the total weight of the edible product, excluding the weight of the packaging.

Table 2. Capacity of end-products per FU and associated market prices.

	Production (kg)	**Market price (€/kg)**	**Data source**
Canned tuna	486.6	24.88	Primary information
Tuna pâté	15.4	26.96	Primary information
Fishmeal	172.2	0.55	Mullon et al. (2009)
Fish oil	36.1	0.61	Mullon et al. (2009)

3. Results and discussion

3.1. Environmental performance of the canned tuna value chain

According to the results shown in **Figure 2**, most of the environmental burdens are produced by two subsystems: SS1 on Tuna fishery and SS2 on Canning process. Thus, the combined contribution of these two subsystems accounts for an average of 94% of the impact in all impact categories, with a minimum of 87% in the ME category and a maximum of 99% in TA. The individual contribution of SS1 is variable, ranging from a minimum of 8.6% in ME to a maximum of 89.9% in TA. Regarding the SS2, it is especially relevant in the MRS and ME categories, with 89.9% and 78% of total contributions, respectively. The environmental impact of SS3 on By-products valorisation is fairly constant in all impact categories, always below 1%, except for the FE and ME categories. A contribution of 4% stands out in the ME category due to the treatment of wastewater generated in the valorisation process. Finally, regarding the production of tuna pâté (SS4), the environmental impact is variable and ranges from 0.8% in TA to the maximum reached in ME with 9.5%. This high value is again reached due to the treatment of the wastewater produced in the processing plant.

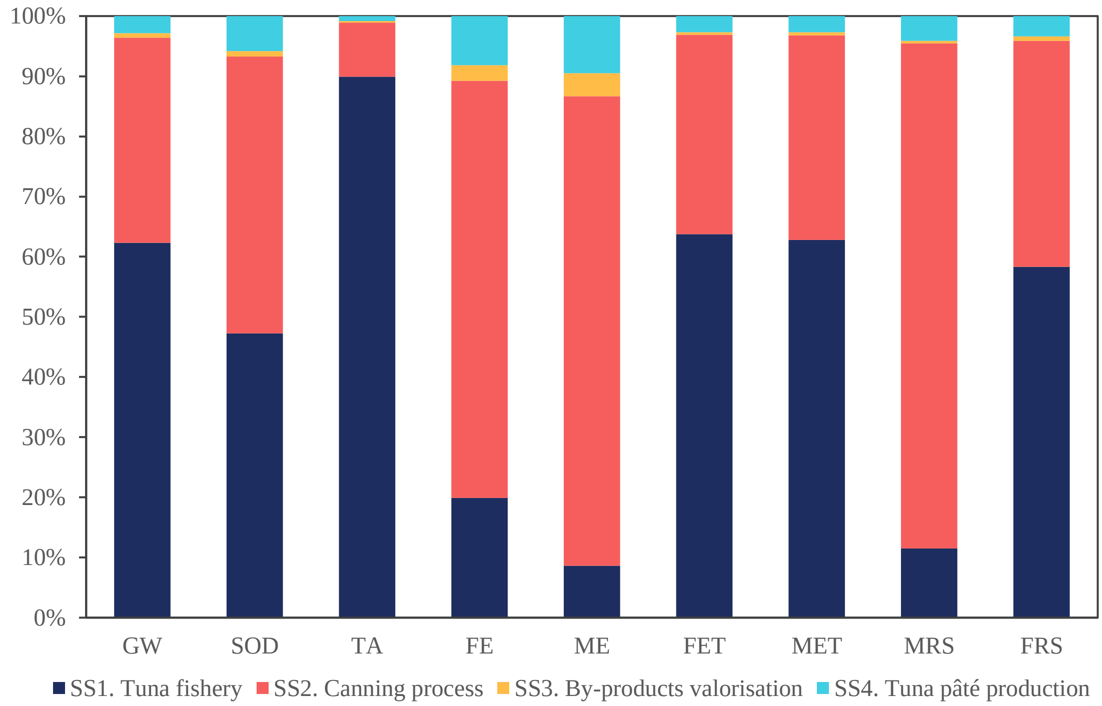

Figure 2. Relative contribution to environmental impacts associated with the canned tuna value chain.

Since most of the environmental impact of the entire value chain is produced in SS1 and SS2, **Figure 3** provides a complete breakdown of the processes involved in these sub-systems. When comparing the pole-and-line tuna fishery in FAO 34 waters with other published studies, similar hotspots are observed: mainly fuel production and consumption, antifouling production and consumption, and GHG emissions of the refrigerant gas (Abdou et al., 2020, 2018; Vázquez-

Rowe et al., 2011b), and bait fishing and processing (Vázquez-Rowe et al., 2014). As can be observed in **Figure 3.a**, fuel production and consumption during fishing operations turned out to be one of the main sources of environmental impact, accounting for more than 83% of the total impact in the TA category, 78% in FRS and 65% in GW. This result was expected and is in line with other fishing fleets revised, where direct and indirect fuel emissions were highlighted as the most important carrier of GHG emissions (Avadí et al., 2018; Sandison et al., 2021; Vázquez-Rowe et al., 2014; Villanueva-Rey et al., 2018), as well as other environmental impacts, such as terrestrial acidification (Ziegler et al., 2016). In this article, a Fuel Use Intensity (FUI) of 548.9 L/tonne was obtained for pole-and-line tuna fishing. This result can be compared with different results published in scientific literature; e.g. Miller et al. (2017) estimated the fuel consumption of the Maldivian pole-and-line fleet among different shoal of tuna, varying from 200 L/tonne to almost 600 L/tonne.

It is worth noting that special emphasis is placed on the fact that bait accounts for approximately 15-20% of the amount of fuel consumed in a fishing trip, which coincides with the results obtained in this study, since the impacts associated with fishing and bait production reach 71.6% in ME and do not fall below 16% in any impact category. Pole-and-line tuna fishing methods have not been traditionally studied, so there are only a few studies that quantify the fuel consumption of this type of fishing gear with different target species, however, tuna fishing by different fishing gears has been extensively studied. In this context, Hospido and Tyedmers (2005) quantified the fuel consumption of the Spanish tuna purse seine fishing fleet in the Indian (373 L/tonne), Atlantic (442 L/tonne) and Pacific (442 L/tonne) oceans, setting the framework for the quantification of FUI of other fisheries in the future. Moreover, Parker et al., (2015) achieved a significantly larger sample of vessels to update this result, obtaining on average that the tuna purse seine fishery consumes on average 365 L/tonne.

Specifically, the purse seine fishery for skipjack tuna in Atlantic waters requires a fuel consumption of 445 L/tonne according to their results. On the other hand, Parker and Tyedmers (2015) estimated a fuel consumption of 1,612 L/tonne for large pelagic (mainly tuna) fisheries using longlines and other forms of pole-and-lines. From another, much more generic point of view, Parker et al. (2018) calculated the global CO_2 emissions linked to fuel combustion in fishing vessels, estimating the FUI of pelagic fish (> 30 cm) at 430 L/tonne. In brief, most of the values provided for tuna fishing, except for longlines, are within the same range, which can give the idea that the values obtained in this study are close to reality. However, it is important to note that FUI measurements from previous studies may vary considerably depending on both the measurement method and the analysed fishing gear (Parker et al., 2015).

On the other side, the production and consumption of antifouling has been revealed as a differential element in the ecotoxicity categories (74.5% in FET and 71% in MET) due to copper and zinc emissions during the use stage, as demonstrated in previous literature (Avadí and Fréon, 2013). It is also noteworthy the 20% of total fishing impact in MRS category, due to the extraction of bauxite to produce cooper needed for antifouling formulation. The bauxite ore is treated with dilute sulphuric acid over a period of months, dissolving copper to form a weak solution of copper sulphate, from which copper can recovered by electrolysis. Ice production contributes much less to the environmental burdens of the system, its contribution remains almost constant in all categories ranging from a minimum of 0.5% to a maximum of 2%, except in the FET category, where it reaches a maximum of 7%, mainly due to electricity consumption and the high dependence on coal in the Spanish electricity profile. Within the GW category, the presence of R-410A stands out, which is a refrigerant gas widely used in refrigeration machines and whose leakage influences the carbon footprint of the process, as has been shown in previous literature (Vázquez-Rowe et al., 2011b). Finally, the environmental impact of paint consumption is practically negligible, while the treatment of the waste (both solid and liquid) is only remarkable in the ME category due to the treatment of bilge wastewater.

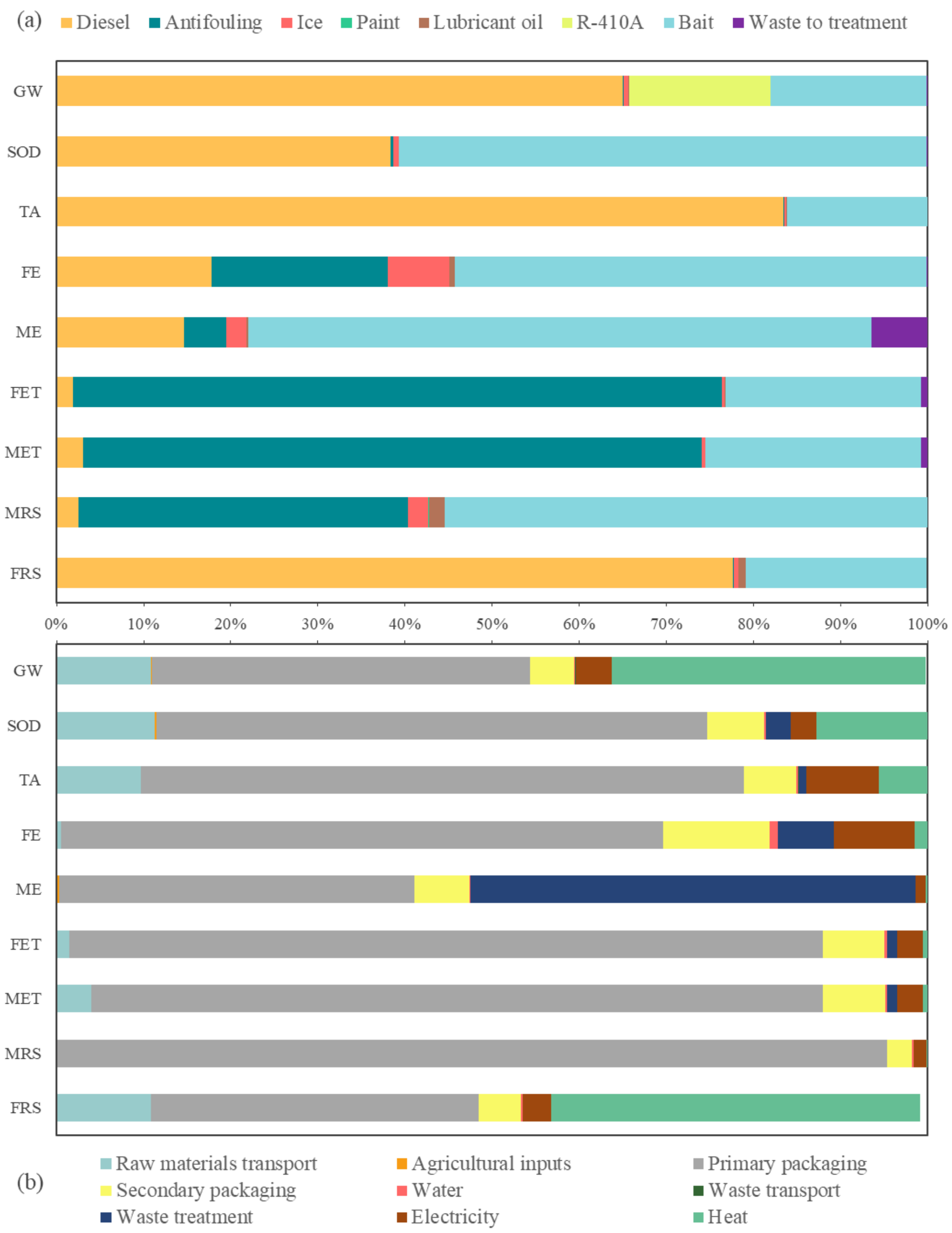

Figure 3. Relative contribution to environmental impacts associated with Subsystem 1. Tuna fishery (a) and Subsystem 2. Canning process (b).

According to the results shown in **Figure 3.b**, the largest contribution to the environmental impact in 6 of the 9 impact categories analysed comes from the production of aluminium primary packaging, proving to be one of the most important elements in the production of canned seafood

(Almeida et al., 2014; Hospido et al., 2006). In fact, the production of aluminium cans is the main contributor to the MRS category, where it reaches the highest contribution to any impact category (95%), linked to the production of virgin aluminium, which requires a high consumption of bauxite (almost 5 kg per kg of aluminium) (Laso et al., 2017). Heat production by natural gas (for cooking and sterilisation) is also an important contributor to GW (36.2%) and FRS (43%), although its contribution to the other categories is in all cases less than 5%. Wastewater treatment, as in the fisheries subsystem (**Figure 3.a**) is only relevant in the ME category (50%) due to nutrient emissions of the treated effluent, while in the other categories, it hardly exceeds 6%. The production of secondary packaging (cardboard and plastic) presents a relative constant contribution around 5-7%, reaching 12.2% in FE and dropping to 2.9% in MRS. Electricity consumption is almost negligible, only relevant in the FE and TA categories (9.2% and 8.3%, respectively), while in the rest of the categories it hardly exceeds 4%. Finally, the production of the agricultural ingredients for the garnish and seasoning (onion, garlic, pepper, etc.) and the transport of waste to specialised plants have a very low contribution in all impact categories, always below 0.5%. The numerical results related to the FU can be found in the Table S.4 of the supplementary material.

3.2. Effect of the allocation strategies on the environmental profile

This study has assessed the entire canned tuna value chain from an environmental point of view, from the production of raw materials to the processing of products and co-products and the treatment of waste, trying to move towards the target of 0 bio-waste. This study is an example of system expansion to avoid the use of allocation strategies, as prioritised in the ISO standards. However, when the objective of the study is to analyse the environmental impacts associated with a particular product within the value chain, and full segregation of material and energy consumption for each production line is not possible, the use of allocation factors to accurately report environmental burdens seems unavoidable (Ayer et al., 2007). Traditionally, the selection of allocation factors is one of the procedures that generates the least consensus among LCA practitioners. In this regard, different authors have proposed different allocation methods for different case studies. Within the seafood-specific case studies, for example, Thrane (2006) used system expansion strategies to handle the co-product allocation in the LCA of different fish products. On the other side, Ziegler et al. (2003) applied economic allocation factors to calculate the environmental burdens of cod fillets, but also they applied mass allocation considering that price fluctuations may condition the reliability of the results. On this basis and considering that the main objective of the canning industry is the production of marketable products that generate an economic income, the economic allocation was calculated for canned tuna (95.8%), tuna pâté (3.3%), fishmeal (0.7%) and fish oil (0.2%).

When analysing the environmental profile of the main product (canned tuna), one different approach from system expansion corresponds to the exclusion of subsystems SS3 and SS4 from the system boundaries, including within the boundaries of SS2 the organic waste treatment processes corresponding to the co-products (635 kg per 1,000 kg of raw tuna). However, this approach would not be entirely realistic, as currently, the processing of fish co-products into fishmeal and fish oil for feed formulation is a widely used option for the treatment of bio-waste. In any case, **Figure 4** shows the variation in the environmental profile of the original value chain (Base scenario) compared to the scenario in which only tuna fishing and processing to produced canned tuna is included, but the valorisation of organic waste from the processing is excluded (Non-circular scenario).

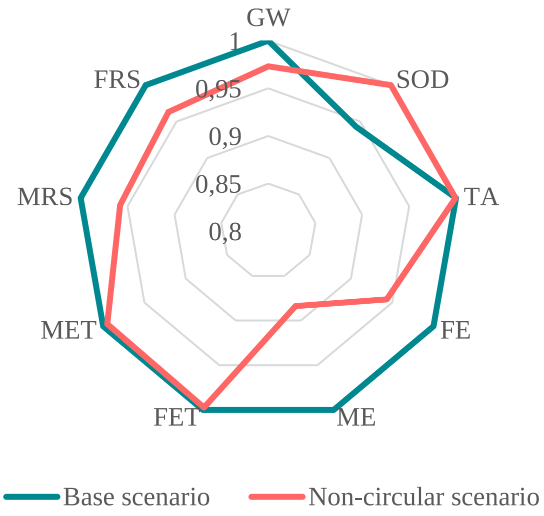

Figure 4. Comparative environmental profile of the two alternative canned tuna production scenarios.

It seems obvious that removing SS3 and SS4 with all associated material and energy consumption from the system boundaries will reduce the environmental impact of the entire value chain. Especially relevant is the reduction in the categories ME and FE, where the contribution of the SS4 subsystem was higher due to the environmental burdens of wastewater treatment, as can be seen in **Figure 2**. However, it is remarkable that the impact of the non-circular approach is almost equal to that of the baseline scenario in the categories of MET, FET and TA. Even more remarkable is that the impact on the SOD category is higher in the non-circular scenario, as the emissions from bio-waste treatment are higher than the emissions from the inputs and outputs of SS3 and SS4.

In order to relativise the impacts of the system towards the production of canned tuna, in the case of the baseline scenario it is necessary to apply economic allocation factors, while for the non-circular scenario, the entire environmental burden is allocated to canned tuna, as it is the main output of the system. Considering that only 365 kg out of 1,000 kg are canned and that 90 g of tuna and 30 g of additive are put into each can, the carbon footprint of a can of tuna was quantified as 0.98 kg CO2 eq in the baseline scenario (considering the economic allocation of all co-products), while in the non-circular scenario it reached 1.01 kg CO_2 eq per can. To give a broader value and not so focused on the carbon footprint, the total environmental impacts were calculated in terms of the ReCiPe methodology endpoint, ranging between 0.050 and 0.052 pts per can in the baseline scenario and in the non-circular scenario, respectively.

In this way, the comparison between the environmental profile of the system evaluated in Figure 1 (Base scenario) and this new scenario (Non-circular scenario) allow to answer the question: is the application of multi-product strategies environmentally viable when the objective of the assessment is to assess only one of the products, without considering the products avoided and the environmental credits? In the specific case studied and taking into account that the inclusion of SS3 and SS4 has not had much influence on the total impact of the system (less than 6% on average), the distribution of the loads between the 4 different products has made it possible to reduce the life cycle impact of canned tuna, while the environmental performance of the whole value chain is hardly modified. It can be seen that a circular economy approach is feasible and effective and these principles are in line with those mentioned by the European Commission in the Circular Economy action plan (European Commission, 2020b).

3.3. Benchmarking with other canned seafood

When comparing with other results available in the peer-reviewed literature, it is important to note that there are some issues that need to be addressed in detail in order to make realistic comparisons (Avadí and Fréon, 2013; Vázquez-Rowe et al., 2012a): (i) The life cycle impact methodology should be detailed since, although the categories of different methodologies may be analogous, in many cases the units of measurement are different; (ii) The functional unit selected for the analysis, as well as the edible content of each product, to adequately estimate the associated environmental impact per unit and per quantity of product (e.g. 1 kg); and (iii) the environmental indicator used for comparison (environmental footprint, normalised impact factor, etc.). Taking all this information into account, **Table 3** shows the detailed results of the comparison between the carbon footprint of different canned seafood products.

Table 3. Carbon footprint values for other canned seafood products

Product	Assessment method	Product	kg CO_2/kg	Reference
Tuna	ReCiPe 2016	90 g tuna 30 g additive 20 g can 5 g board	8.2	Present study
Pilchard	CML-IA Baseline	95 g pilchard 35 g olive oil 20 g can	7.5	(Almeida et al., 2015)
Pilchard	ReCiPe 2008	85 g pilchard 35 g olive oil 20 g can	25.2	(Vázquez-Rowe et al., 2014)
Mussels	IPCC 2016	129 g mussels 120 g sauce 81 g can 12.7 g board	17.5	(Iribarren et al., 2010a)
Tuna	ReCiPe 2008	n.d.	3.7	(Avadí et al., 2015)
Peruvian anchovy	ReCiPe 2008	n.d.	1.7	(Avadí et al., 2014)
Cantabrian anchovy	ESA with metrics from ICheme 2002	30 g anchovy 20 g olive oil 15 g can 5 g board	4.7	(Laso et al., 2017)

Is important to note that **Table 3** compiles the results with a cradle-to-gate approach, considering the impacts related to fishing, processing and packaging. Thus, in those studies that considered the distribution and consumption stages (Almeida et al., 2015; Laso et al., 2017; Vázquez-Rowe et al., 2014), the environmental burdens corresponding to these stages were not taken into account.

The carbon footprint of canned tuna presents an intermediate value, much lower than the values presented by sardine in olive oil (Vázquez-Rowe et al., 2014) and mussels, mainly due to the production of the primary packaging, as these two cases were packed in tinplate. However, this value is very similar to the associated with the can of sardines with olive oil assessed in Almeida et al. (2015), where similar packaging is used and similar techniques are followed.

Cantabrian anchovy is also packaged in aluminium and, despite having a much lower fish/package ratio than that obtained in this study, they reported only 4.7 kg CO_2/kg. This is because the processing operations are very different, and the catch ratios of this fishery are much higher. In this sense, the low results for Ecuadorian canned tuna (Avadí et al., 2015) and Peruvian anchovy

(Avadí et al., 2014) can be explained by lower fuel use in the Ecuadorian and Peruvian fisheries, mainly due to a better catch per unit effort in relation to a higher abundance of the resource (Fréon et al., 2014a). While it is true that in all cases it was concluded that both the fishing stage and the production of primary packaging (tinplate or aluminium) are the main drivers of environmental impacts and all improvement actions should focus on them.

4. Conclusions

This study demonstrates that, from a product approach, the inclusion of by-product valorisation processes to address a multi-product strategy improves the environmental profile of the main product. It is a clear example of a system expansion to avoid burden allocation between products when the focus is on the assessment of the entire value chain. When the focus is on the assessment of a single product, the allocation of environmental burdens seems unavoidable.

It has been shown that the fishing and primary processing stages are the most relevant sub-systems within the environmental profile of the canned tuna value chain. The inventory of the fishing stage showed, as previous studies on different fishing fleets, that the impacts of the fishing stage come mainly from the production and consumption of diesel and antifouling. In this case, the importance of the bait used for fishing also stands out, as it requires the fishing and processing of sardine for use as bait. Primary packaging presented the highest environmental impact in the life cycle impacts of canned tuna. Aluminium production, lamination and extrusion had the highest impact in almost all impact categories, as expected for canned products. By-product valorisation processes, both edible and inedible, have proven to have a low impact.

This system has allowed an approximation of the EU target towards a cradle-to-cradle system approach, achieving the goal of zero biowaste. The results show the need to improve the application of the circular economy in the primary sector, converting waste into raw materials for the production of new products, minimising the consumption of material and energy resources. In this sense, the application of multi-product strategies has been shown to improve the environmental profile of canned products through the allocation of environmental burdens among the new products; although further analysis from a sustainability point of view is required. Similar studies need to be further applied to specific primary sub-sectors in the future to continue the path towards a more sustainable and circular food system.

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