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Contribution of glass jar packaging to the environmental assessment of canned seafood products: Albacore tuna (*Thunnus alalunga*) and Atlantic chub mackerel (*Scomber colias*) as case studies

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ABSTRACT

Canned seafood is a practical option for consumers with high nutritional value. However, packaging plays a key role in its environmental impacts due to the production of metal cans made by aluminium or tinplate and glass jars. The aim of this study was to perform a life cycle assessment of four seafood canned products in glass jars with Atlantic chub mackerel and albacore tuna. The contribution of end-of-life options for glass jar (reuse, recycle or landfill) was also evaluated, as well as environmental burden of storage at home scenarios of canned, chilled and frozen fish productspotential seafood waste in the different supply chains.

Glass jar packaging contribution to environmental assessment of products was half compared with metal cans. The production of ingredients was the life cycle phase with highest contribution in all products followed by primary packaging for climate change impact category. Results pointed out the benefits of recycling glass jar with 8% GHG emissions reduction on average. Storage at the consumer stage represented less GHG emissions for canned products when compared to frozen when considering a period of more than one month.

1. Introduction

The environmental performance of seafood products depends not only on the fishery or aquaculture production phases, but also on the different degrees of processing and packaging (Vázquez-Rowe et al., 2012). Therefore, indirect effects related to the extension of shelf-life and relative food waste reduction, can lead to different conclusion and thus strategies for the packaging choice (Casson et al., 2022). Besides its economic and social importance, fresh and processed marine products are greatly present in the Atlantic regions' diets. Portugal and Spain stand out as the major EU consumers of fishery and aquaculture products, with 57.7 kg and 44.2 kg per capita, in 2021, respectively, while the EU average is 23.3 kg per capita (EUMOFA, 2022). Thus, any potential improvement in the seafood supply chain can have a significant contribution to reduce environmental burdens from seafood consumption in these countries.

Canning is a preservation process that consists of packing products in containers hermetically sealed and subject to sterilization, guaranteeing the products quality during prolonged periods (Sousa et al., 2018). Spain is the top European producer of canned food, producing almost 70% of canned tuna in the European Union (EU), which represents around two-thirds of the produced volume and one-half of the value (GLOBEFISH, n.d.). In 2020, Spain produced 359,081 tons of canned seafood products, with tuna being the principal product (69%), followed by sardines (7%), mussels (4%), and mackerel (4%) (ANFACO-CECOPESCA, 2021). In Portugal, the production of canned seafood products reached 60,565 tons in 2020, and it is distributed mainly by 3 group species - tuna (42%), sardines (16%), and mackerel (5%) - and a variety of sauces (e.g., olive oil, other vegetables oils, or tomato sauce) (INE, 2022).

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In addition to the evolution in the product diversification, the canning sector has been following environmental concerns by using fish from stocks with certification (e.g., MSC certification) or recyclable packaging with the implementation of circular economy best practices (Sousa et al., 2018). The standardised Life Cycle Assessment (LCA) methodology has proven to be the most established scientific tool to quantify potential environmental burdens of seafood products along its supply chain (Ruiz-Salmón et al., 2021). A responsible use of raw materials, prevention of waste, and efficient use of energy and packaging along the supply chain can result in economic and environmental savings (Bugallo et al., 2013). In fact, several LCA studies about canned seafood products have identified packaging – metal cans made by aluminium or tinplate and glass jars – as a hotspot in the environmental impact of this type of products (Almeida et al., 2021). To reduce the environmental challenge associated with packaging in canned products life cycle, LCA methodology delivered useful results by adding materials from a life cycle perspective including their production, recyclability prospects, or substitution by innovative packaging materials (Ruiz-Salmón et al., 2021). For example, Hospido et al. (2006) and Avadí et al. (2015) proposed cans recycling, and Almeida et al. (2015) proposed the use of alternative packaging materials to reduce environmental impacts from seafood canned products. Most LCA studies about canning products included aluminium or tinplate packaging (Almeida et al., 2021). Only canned anchovy LCA study of Laso et al. (2017) included primary life cycle inventory data for glass jars, which presented lower impact in almost all environmental impact categories compared with aluminium can.

Glass jar packaging is used for higher quality products and allows consumers to visualize the content, thus increasing consumers' confidence in product quality. When compared to metal cans, a greater part of glass jars processing is done manually. Glass jars are made of 100% recyclable material, can be re-used for other purposes, and allow product storage after opening. However, there are disadvantages when compared to aluminium cans related with a higher economic cost and shorter shelf-life of products (only 2 instead of 5 years). Also, glass is more fragile and heavier than metal, and piling of glass jars is more difficult, which are important characteristics for transport and storage.

This study aims to evaluate the environmental impacts by means of the LCA methodology of four canned seafood products in glass jar prepared in three different factories in 2019. Two products were produced in Portugal with Atlantic chub mackerel (*Scomber colias*), and other two produced in Spain with albacore tuna (*Thunnus alalunga*). The research has the novelty of bridging the gap by addressing canned seafood in glass jar packaging and including Atlantic chub mackerel species for the first time in an LCA study. Canned products present benefits compared to frozen or chilled supply chains in terms of conservation without the need for refrigeration, and less seafood waste during post-production storage (Almeida et al., 2015). However, this was never assessed from a holistic approach in an LCA study. Therefore, the study aims to 1) identify the contribution of glass jar packaging in seafood canned products environmental assessment, 2) quantify the contribution of different end-of-life (EoL) options for glass jar packaging (reuse versus single use with recycling or landfill), and 3) evaluate the environmental burden through time of canned products compared with chilled and frozen fish products considering an average storage at home together with the potential seafood waste in the different supply chains. The outcomes of this work will be helpful for the seafood sector to improve knowledge on the environmental assessment of canned products in glass jars, adding valuable information to the final consumer and raising awareness on packaging EoL choice importance to the overall assessment. Moreover, these remarks can be useful for decision-makers in the current context of sustainable policies.

2. Material and methods

2.1. Goal and scope

The LCA framework (ISO, 2006a, 2006b) was applied to assess environmental impacts of four canned products in glass jar made with Atlantic chub mackerel and albacore tuna, from production phase until the processing factory gate (i.e., cradle-to-gate with end-of-life approach).

- Product #1 is canned Atlantic chub mackerel (*Scomber colias*) with olives and almonds (100 gr net weight from which 14% corresponds to olives, onion, lemon juice; and 6% to almonds and olive oil). The company has its facilities in Portimão (Portugal), and commercializes different types of canned products in glass jars and metal cans. It follows the traditional canning method, where the fish is cooked before being canned. Procedures are all done manually as, for example, glass jars are filled and sealed by hand before going to the sterilization equipment.
- Product #2 is a canned product made with Atlantic chub mackerel and Pacific mackerel (*Scomber japonicus*) in olive oil in a glass jar (250 g net weight from which 34% is olive oil). Both species have a similar appearance and for the purposes of this manuscript the name used will be always Atlantic chub mackerel. The company has its facilities in Vila do Conde (Portugal); commercializes canning products made with Atlantic chub mackerel, tuna, and salmon; and follows the industrial method with machinery in all steps except in fish processing, where it is necessary to cut and clean fish fillets by hand in order to fill the jars with an adequate quantity of fish.
- Product #3 is canned albacore tuna (*Thunnus alalunga*) in olive oil in a glass jar (360 g net weight from which 28% is olive oil) and product #4 is albacore tuna in brine water (without additives) in a glass jar (360 g from which 28% is brine). Production of both products takes place in a processing plant located in Santoña, in Cantabrian region (Spain); and includes all operations from transforming fresh tuna into the processed products following the industrial method, with machinery in all steps.

The products come from different sources/factories and even though product #1 is a multi-ingredient product, ingredients as olives, onion and almonds function as seasoning, and its percentage of fish is 80% compared with 66% in product #2 and 72% in products #3 and 4#.

Postproduction phases of canned products are assumed to have low importance, as cans do not need refrigeration and energy for illumination or air conditioning could be negligible. Also, given that canned seafood does not necessarily need to be cooked, assumptions in the consumption phase can be in some way inaccurate (Iribarren et al., 2010). Therefore, this study excludes distribution and consumption phases, where there is higher uncertainty.

Three end-use phase scenarios were developed to quantify the contribution of different EoL possibilities for glass jars packaging, including: 1) reuse of the glass jars, 2) single use sending 100% or 50% of the packaging to recycling end-of-life treatment, and 3) single use sending packaging to landfill end-of-life treatment. To evaluate the environmental burden of canned seafood products through time, considering their longer shelf life and storage without refrigeration, three scenarios where also developed to compare storage at home of 1) canned at room temperature, 2) chilled, and 3) frozen fish products.

The products were compared in the way they are used at the consumption phase and in a quantity to compare easily with other products. The functional unit (FU) used was 1 kg of product packed, including the jars, sauce and additives. The data was collected via site visits, where a survey was filled with the main information. The systems boundaries start at the production of ingredients, including the fishing phase, and finish at the factory gate.

2.2. System description

The system boundaries and main flows from the four products are summarized in Fig. 1. On the one hand, the system of product #1 includes the production of Atlantic chub mackerel from purse seine fishing in Portugal, while the system of product #2 comprises fish from purse seiners sourced in Portugal (18%), Spain (35%), and Peru (47%). In the case of products #3 and #4 albacore tuna comes from purse seine and artisanal fishing in the Cantabrian coast. Other ingredients used such as olives, onion, lemon juice, almonds, olive oil, brine or salt were assumed to be sourced at the national level and transported by road.

The processing starts with the reception of ingredients in the factory. All products are stored in the warehouse and fish is kept in a refrigeration chamber. Fish in products #3 and #4 go firstly through a process of filleting and later pass, as product #2, by a brine beforehand. The subsequent common step is the cooking phase, where the fish is steamed in an industrial oven. Once the fish is cooked, the loins are taken and by-products (e.g. bones, heads, skin, fins) are separated manually. During the preparation, all ingredients and seasonings are mixed, and jars are filled. The filling and weighting process of product #1 is carried out individually and manually, while in the remaining products these operations are completed mechanically. In the next step, jars/cans go to an autoclave equipment to sterilize the final products. Products #1 and #2 have a label with information made in paper that is placed around the jars. Cardboard boxes corresponding to secondary packaging are used to pack the final products.

The water used in the factories is tap water. The energy source used in the plants is electricity, with the exception of diesel fuel used to heat water in the cooking phase of products #3 and #4. Effluents from factories, including liquid losses, go to sewage municipal treatment with the exception of oil waste in the plant of products #3 and #4, which is collected by an authorised agent. Waste as glass, lids of aluminium, cardboard from packaging, and plastic bags from fish transport are sent to recycling waste treatment in the case of products #1 and #2, and to municipal disposal in products #3 and #4. The factory in system #2 also produces mud waste that is sent to a refinery sludge to produce biodiesel. By-products are sent to another factory that produces animal feed, but all resources from fish production were allocated to canned products since those by-products are generated only because fish is processed in the canning industry. Capital goods of canning factories were excluded on the basis of their long lifespan, but also owing to machinery complexity.

2.3. Assumptions, limitations and modelling decisions

Product #1 is produced only with fish caught in Portugal coming from purse seining fishery. The study from Almeida et al. (2014) was used as a reference for modelling (e.g., consumption of diesel, lubricant for the engine, and ice for vessel operations). Product #2 is produced with fish caught in Portugal, Spain, and Peru transported by boat until Leixões harbour and by road afterwards until the canning factory. Data for fishing operations was also based on the study from Almeida et al. (2014) as a reference for Portuguese and Spanish sources since fishing operations in both countries are very similar (Vázquez-Rowe et al., 2014). Ecoinvent database v3.5 was used for Peruvian fish source through data for whole and fresh fish captured by anchoveta Peruvian purse seine fleet (Avadí et al., 2020), which also catches Pacific chub mackerel (Christensen et al., 2014). Captures are stored with ice on board until fish are landed for auction sale. Products #3 and #4 are produced with albacore tuna, being 80% of the fish used caught in the Cantabrian coast by purse seiners (62%) and longline/gillnets (38%). Data used for these two fishing fleets were based on Ceballos-Santos et al. (2023) study. None of the fishing fleets uses refrigerants in their operations as vessels do not have ice machine or other equipment that uses refrigerants.

It was considered for all fish production sources that nylon nets have a lifespan of about five years and 25% are renewed every year (Vázquez-Rowe et al., 2012). Vessel maintenance included only paint and followed the ratio of values reported by Vázquez-Rowe et al. (2011). Ice is provided by fishermen's guilds or fish auction installations, and data for ice production were obtained from Almeida et al. (2014). Emissions resulting from diesel combustion on boat engines were obtained on emission factors for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) based on the IPCC database related with mobile combustion (Eggleston et al., 2006). Whereas emission factors specific for air pollutant emissions related to maritime navigation as sulphur

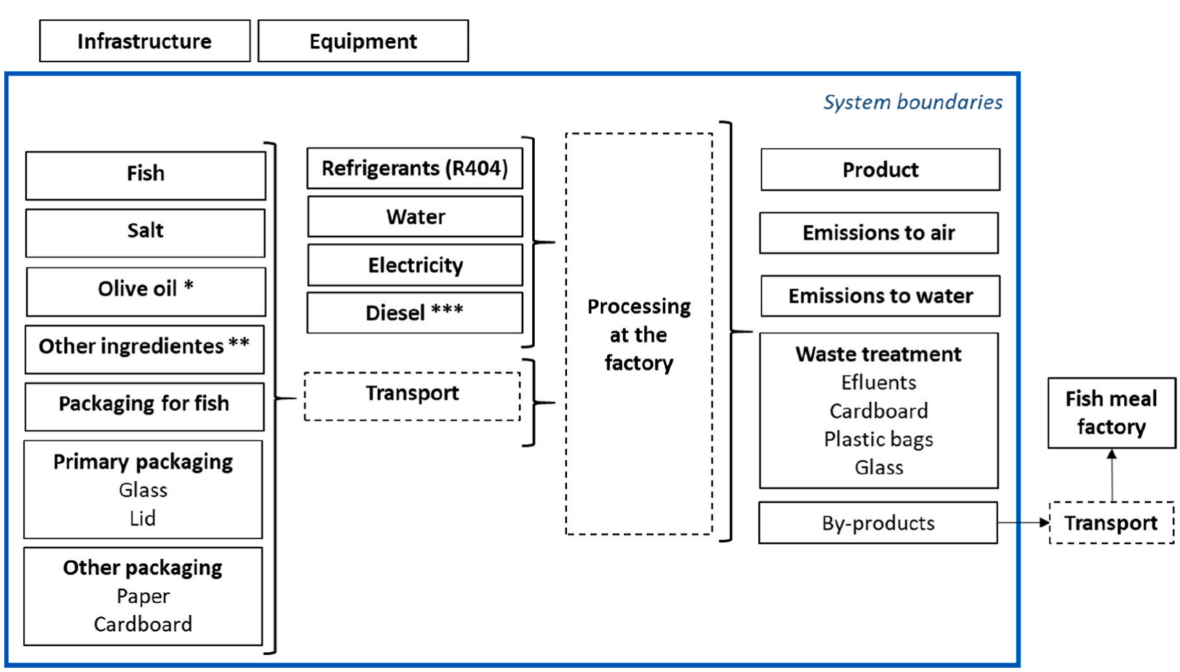

Fig. 1. System boundaries of the studied products (* olive oil is not included in product #4; ** only product #1 has other ingredients apart from fish, including onions, almonds, lemons; *** only product #3 and #4 use diesel).

dioxide (SO_2), particulate matter (PM), nitrogen oxides (NO_x), and production and emission factors for engine oil combustion, were collected from the EMEP-Corinair Emission Inventory Handbook (EMEP/EEA, 2019). All data included are listed in the supplementary material (Tables SM1, SM2, SM3, SM4, SM5). The fish distribution from the harbour to canning factories was included to link fishing ports to processing facilities. The refrigerant used in the factory of product #1 is 404a, which is made by three other refrigerants (143a, 125, and 134a). In the case of product #2 it is 422d and 404a, but only 404a was considered because it was the only process available in Ecoinvent database v3.5. The use of refrigerants was not included in products #3 and #4 life cycles as the factory only works with fresh fish.

Allocation could not be avoided and the burdens were divided within the system, i.e., among the different products, based on mass allocation regarding the use of general inputs from the factory. Economic allocation was not used to avoid uncertainties related to economic revenues, which varies according to the market and end customer (Ziegler et al., 2013). Most of the data were given for total production and allocated regarding the percentage in the total production represented by each product: 16%, 14% 10% and 8% for products #1, #2, #3, #4, respectively.

2.4. Life cycle inventory

The data collection is presented in the life cycle inventory for 1 kg of edible product, corresponding to the FU. All materials, activities, and processes associated with the target products were identified and quantified in Table 1. Primary data was collected for factory operations with site visits. Background data was used for electricity, water, transports, diesel, refrigerants, paint, lubricant, packaging, ingredients, and waste management. Data was retrieved from the Ecoinvent v3.5 database (Moreno et al., 2018) and for olives and olive oil production based on AGRIBALYSE v3.0.1 database (Asselin-Balençon et al., 2020). Processes used for each input and output are described in Tables SM6, SM7,

Table 1
Inventory data for the four products studied (values per FU = 1 kg of edible product).

INPUTS			Product #1	Product #2	Product #3	Product #4
Materials	Fish (*Scomber colias*) from purse seine fishing	kg	1.70	–	–	–
	Fish (*Scomber colias*) from purse seine fishing sourced in Portugal	kg	–	0.62	–	–
	Fish (*Scomber colias*) from purse seine fishing sourced in Spain	kg	–	1.21	–	–
	Fish (*Scomber japonicus*) from purse seine fishing sourced in Peru	kg	–	1.62	–	–
	Fish (*Thunnus alalunga*) from purse seine fishing sourced in Cantabria (Spain)	kg	–	–	1.83	1.83
	Transport of fish from harbour to plant (road)	km	20	160	–	–
	Transport of fish from harbour in Peru to Portugal (ship)	km	–	10,364	–	–
	Transport of fish from harbour in Portugal to plant	km	–	30	–	–
	Transport of fish from the Cantabrian ports to the factory	km	–	–	136	136
	Salt	kg	–	0.12	–	–
	Onion	kg	0.17	–	–	–
	Transport of onions	km	5	–	–	–
	Olive	kg	0.30	–	–	–
	Transport of olives	km	80	–	–	–
	Olive oil	litres	0.07	0.25	0.96	–
	Transport of olive oil	km	80	–	780	–
	Almond	kg	0.08	–	–	–
	Transport of almonds	km	70	–	–	–
	Lemon	kg	0.51	–	–	–
	Transport of lemons	km	9	–	–	–
	Refrigerants (R404)	litres	0.0001	0.0001	–	–
	Brine	kg	–	–	0.54	0.54
	Transport of brine	km	–	–	225	225
Energy	Electricity	kWh	2.20	0.48	0.003	0.003
	Energy - Natural gas	kWh	–	1.69	–	–
	Diesel	litres	–	–	0.15	0.15
Water	Water	m^3	0.11	0.02	0.01	0.01
Packaging	Packaging - plastic bag for fish - LDPE	kg	0.03	0.01	–	–
	Packaging - container in glass (100 gr per unit)	kg	1.18	0.81	0.61	0.61
	Transport of glass	km	250	350	1500	1500
	Packaging - lid in metal	kg	0.10	0.04	0.05	0.05
	Transport of lids	km	250	1952	1500	1500
	Secondary packaging - paper	kg	0.05	0.09	–	–
	Transport of paper	km	280	45	–	–
	Tertiary packaging - carboard box	kg	0.20	0.06	0.04	0.04
	Transport of carboard box	km	350	45	65	65
OUTPUTS						
Product	Atlantic chub mackerel with olives and almonds	kg	1.00	–	–	–
	Atlantic chub mackerel in olive oil	kg	–	1.00	–	–
	Albacore tuna in olive oil	kg	–	–	1.00	–
	Albacore tuna natural	kg	–	–	–	1.00
Waste and emissions to treatment	Effluents	m^3	0.02	0.01	0.01	0.01
	Fish by-products and losses (not included in the system)	kg	1.00	1.87	0.77	0.77
	Cardboard	kg	0.04	0.09	0.01	0.02
	Glass jars	kg	–	0.005	0.05	0.07
	Plastic bags	kg	0.03	–	–	–
	Metal (including tin plate and other metals from capsules, old equipment)	kg	–	0.01	–	–
	Mud and organic waste	kg	–	0.25	–	–
Emissions to air from fishing	Carbon dioxide	kg	0.50	1.01	0.58	0.58
	Methane	g	0.05	0.10	0.05	0.05
	Dinitrogen monoxide	g	0.01	0.03	0.02	0.02
	Nitrogen oxides	kg	0.01	0.03	0.01	0.01

SM8, and SM9.

2.5. Life cycle impact assessment

The life cycle impact assessment was carried out using the method EF 3.0 (adapted) v1.01 (Fazio et al., 2018). Eight conventional impact categories were selected and analysed according to the type of impacts more frequently applied in seafood LCA studies (Ruiz-Salmón et al., 2021): climate change (CC) and ozone depletion (OD) to establish the impacts on the atmosphere and the ozone layer related to gaseous emissions; freshwater eutrophication (FE), marine eutrophication (ME), water use (WU) and freshwater ecotoxicity (FET) to quantify impacts on fresh and marine water; and fossils resource use (FRU) and minerals and metals resource use (MMRU) to establish a link with minerals used in glass jars and fuel consumption as it is a main hotspot in fishing activities (Parker et al., 2018). SimaPro v9.2 (PRé Consultants, 2021) was the software used to lead the computational implementation of life cycle inventories. Results were aggregated by categories: fish production – fishing, other ingredients production, transport of ingredients, factory operations, packaging, and waste treatment.

2.6. Analysis of climate change impacts for different end-of-life scenarios

The contribution of different EoL options was tested with three scenarios. The first one considered glass jars were reused for a different purpose or product. Therefore, the glass material production load was divided by two, corresponding to two possible products/uses, and it was assumed that half of glass jars load was allocated in a new product modelling out of the system boundaries. Furthermore, the jars washing was included with energy and water consumption data per item washed in a dishwasher based on Richter (2011). A second scenario was prepared as if glass jars would be sent to recycling waste treatment and the corresponding avoided glass material was equally added. In this case two options were analysed considering 100% or 50% of recycled material used. The third scenario considered glass jars were sent to a non-differentiated waste disposal bin and it was assumed that it will be sent to landfill waste treatment. The background processes regarding electricity and water production, or waste treatments were added from the Ecoinvent database v3.5 (Moreno et al., 2018) (Table SM10). Results were presented only for climate change impact category.

2.7. Comparison of canning, chilled and frozen fish supply chains

To compare canned products with chilled and frozen fish supply chains considering only storage at home phase and including an average shelf-life period for each product, three scenarios were created for 1 kg of edible fish made of Atlantic chub mackerel and albacore tuna. Canned products were assumed to be entirely edible, since only fish fillets are used, and made by 25% of the four products studied. For fresh and frozen fish edible rates for live weight were assumed based on FAO (1989): 65% for Atlantic mackerel and 69% for albacore tuna. Since canned products in glass jars have a shelf life of 2 years, it was considered a storage during 1 year at home. Canned products do not need refrigerated transport or storage, and it is not expected waste along the postproduction supply chain.

To represent a chilled product, a scenario was created where temperature was reduced to 0 °C using ice. The shelf-life will depend on the shape, size, skin and fat content in the flesh of the fish species (e.g., mackerel shelf life can be between 4 and 19 days in ice) (Shawyer and Pizzali, 2003). It was considered that fish came from the same sources as in canned products. The supply chain considered that fish were landed at the harbour, then transported to the fishmonger (with a distance of 100 km), and afterwards stored at home during 3 days. It was added a waste for fresh fish of 5% based on James et al. (2011) and packaging considering a box weighting 490 g that takes 20 kg of fish and 4,5 kg of ice based on data from Winther et al. (2020). The scenario was considered to be in Europe therefore electricity country mix corresponded to Europe.

A third scenario was created for the case of a frozen product, where freezing storage represented a long-term storage (a year or more depending on the species) (Shawyer and Pizzali, 2003). The life cycle included the fishery phase done in the same way as for chilled products, assuming that fish are transported to the processing factory where it will be frozen (100 km distance), and afterwards stored at home for 1, 3 or 6 months. During the freezing process, approximately 3% of the fish is wasted, and electricity, water and refrigerant consumption were based on data from Almeida et al. (2015). It was included an average storage period of frozen fish at the factory of 90 days, as well as packaging made of LDPE bag (0.0004 kg plastic/600 g product) and a secondary packaging of a cardboard box (0.24 kg card board/5 kg product) (Almeida et al., 2015). Hereafter, a transport was considered from the processing industry to the market (100 km distance). Finally, at home, an energy consumption of fridge-freezer equipment with the mean freezer temperature −20 °C was included (1575 kW h.m^3/year) for 1, 3 or 6 months storage of a volume of 0.1 m^3 (Biglia et al., 2018).

3. Results

3.1. Environmental assessment of canned products

The contribution of the different life cycle phases was relatively different between the products for the impact categories selected, except for CC and ME, where production of ingredients had the highest contribution in all products (Fig. 2). Absolute values for each product are presented in SM12, SM13, SM14 and SM15. This contribution was especially high in products #3 and #4, representing 84% and 82% for CC, and 89% and 81% for ME, respectively. In the case of product #3, the production of ingredients, made of albacore tuna, olive oil, and salt, was actually the life cycle phase with highest contribution in all environmental impact categories presented. This was not the case of product #4, even though both products are produced in the same factory. This difference can be justified by the fact that product #3 uses olive oil and; therefore, its production is an extra burden not included in production of ingredients in product #4, which uses only brine as sauce.

The contribution of waste treatments in WU from product #4 presented a negative value of −0.1 m^3 depriv. (−58%) since in this case there is only water added to the system from effluents from the factory and the absence of olive oil, a main difference when compared with the other three products (Table SM15). Olive oil production contributes significantly to increase the level of water used from agriculture operations. The water used in olive oil production offsets water added from effluents from the factory in the outputs of the products using olive oil. Waste treatments also contributed to negative results in WU in the case of products #1 and #3, representing −4% in both cases, but water used was higher in these two products due to the production of other ingredients apart from olive oil, resulting in 17.9 and 10.0 m^3 depriv. for WU, respectively (Tables SM12 and SM14).

Primary packaging production had the highest contribution in some impact categories: in the case of product #1 for OD (32%), FE (41%), and FRU (36%); product #2 for FE (34%); and product #4 for FE (69%), FET (50%), and WU (33%). In most other cases it was the second highest contribution. Transport was the life cycle phase with highest contribution only in the case of product #1 for MMRU (40%) due to a higher number of ingredients and consequently its associated distribution, and product #2 for OD (47%), FRU (41%), and MMRU (70%), due to the greater distance on fish transport which is sourced in Peru.

3.2. Climate change results for different end-of-life scenarios

If we look more in detail to CC results (Table 2), it is possible to confirm that the four products presented a carbon footprint in the same level, ranging between 9.4 and 11.5 kg CO_2 eq. for product #1 and #3,

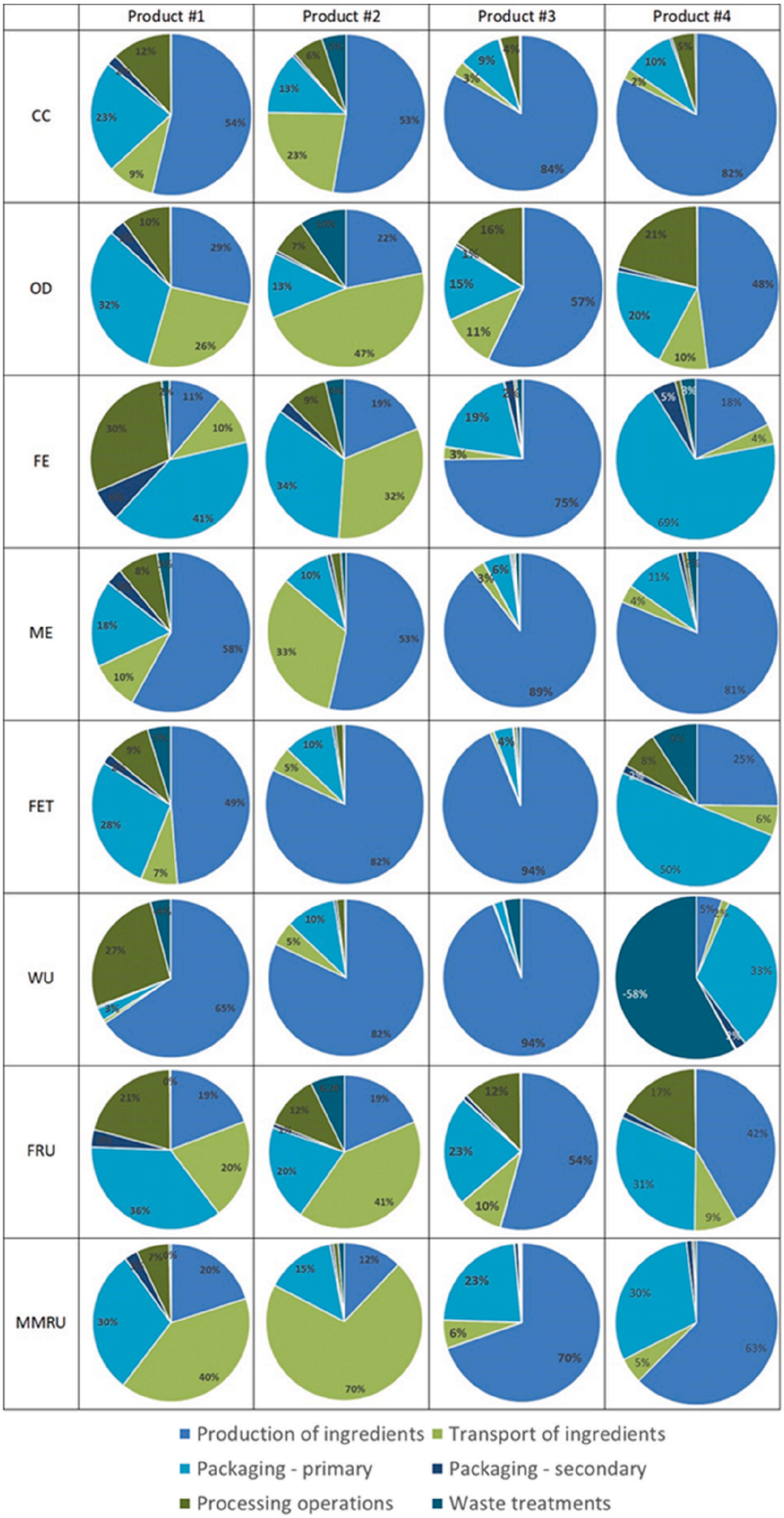

Fig. 2. Relative results of the environmental impact categories for 1 kg of product #1 (Atlantic chub mackerel with olives and almonds), product #2 (Atlantic chub mackerel in olive oil), product #3 (albacore tuna in olive oil), and product #4 (albacore tuna in natural) (CC - climate change (kg CO_2 eq.), OD - ozone depletion (kg CFC11 eq.), FE - freshwater eutrophication (kg P eq.), ME - marine eutrophication (kg N eq.), FET - freshwater ecotoxicity (CTUe), WU - water use (m^3 depriv.), FRU - fossils resource use (MJ), MMRU - minerals and metals resource use (kg Sb eq)).

Table 2
Climate change results to 1 kg of the four canned products studied and the contribution of different EoL scenarios.

		Product #1		Product #2		Product #3		Product #4	
		kg CO_2 eq.	%	kg CO_2 eq	%	kg CO_2 eq	%	kg CO_2 eq	%
Production of ingredients		5.05	54%	5.53	53%	9.60	83%	8.34	82%
Transport of ingredients		0.89	9%	2.36	23%	0.34	3%	0.23	2%
Packaging - primary		2.12	23%	1.34	13%	1.03	9%	1.03	10%
Packaging - secondary		0.19	2%	0.05	1%	0.04	0%	0.04	0%
Processing operations		1.14	12%	0.66	6%	0.47	4%	0.47	5%
Waste treatments		0.01	0%	0.53	5%	0.03	0%	0.04	0%
TOTAL		**9.40**		**10.48**		**11.51**		**10.15**	
End-of-life scenarios	Reuse (1×)	8.89	- 5%	10.12	- 3%	11.69	+2%	10.42	+3%
	Recycling (100%)	7.90	- 16%	9.45	- 10%	11.19	- 3%	9.92	- 2%
	Recycling (50%)	9.10	- 3%	10.27	- 2%	11.81	+3%	10.54	+4%
	General disposal (landfill)	10.30	+10%	11.10	+6%	12.43	+8%	11.16	+10%

respectively. The production of ingredients was the life cycle phase with highest contribution in all products, followed by primary packaging, in this case glass jars, for all products, except product #2, which had transport stage as the second highest burden in CC results. The reason is the fact that part of the fish is sourced in a distant country, Peru, and therefore transport of ingredients resulted in higher emissions comparing with the other products that obtained fish in Portugal and Spain. Primary packaging had the highest contribution in product #1, representing 23% of the total CC (2.1 kg CO_2 eq. per 1 kg of product), due to the net weight of the product, which was the lightest among the four, meaning that more packaging material is necessary for the FU.

Regarding EoL of packaging, recycling 100% obtained the best results, with a range of avoidance between 2 and 16% of the products' GHG emissions, for product #1 and #4, respectively. Landfill represented the worst scenario to all products, representing an increase of GHG emissions between 6% for product #2 and 10% for products #1 and #4. The reuse option of packaging obtained better results when compared with recycling 50% of the packaging material since the part of material not recycled was assumed to go to landfill treatment and GHG emissions from this waste treatment process were added.

3.3. Comparison canned fish in glass jars with alternative supply chains

When canned products were compared with frozen and chilled fish supply chains (Fig. 3), CC results for the three frameworks were higher for frozen products stored during 3 and 6 months. Storage at home phase is highly relevant for frozen products due to electricity consumption. The scenario of 6 months storage represented more than three times the GHG emissions when compared with canned products (38.1 kg CO_2 eq.), representing 87.5% of the total CC result in the frozen supply chain. Compared with chilled fish scheme, this life cycle phase considering 3 days of storage, contributed only with 8.6%. In the canned products

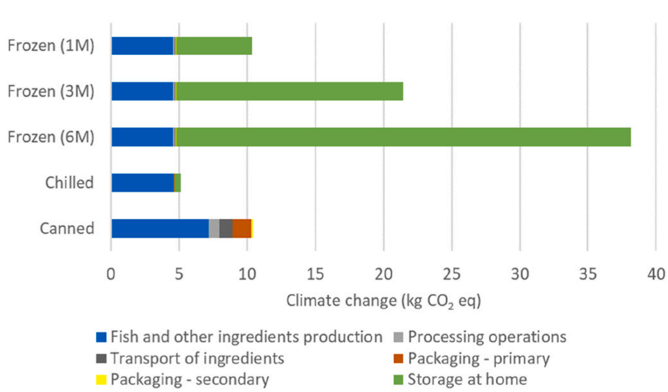

Fig. 3. Climate change results of 1 kg of edible Atlantic chub mackerel and albacore tuna in canned, chilled and frozen during 1, 3 and 6 months processed forms and the contribution of the different storage at home scenarios.

scenario there are no GHG emissions from storage at home. However, canned products represented more than two times of GHG emissions per kg of product when compared with chilled fish due to the fact of having a higher contribution from fish and other ingredients production (e.g. olive oil), including also fish waste associated with those supply chains. Canned products also presented a higher contribution from packaging, transport and have a burden from processing operations almost absent in the other two supply chains.

4. Discussion

4.1. Environmental assessment of canned fish in glass jars and comparison with other packaging materials

The provision of packaging in aluminium or tinplate in seafood products has been stated as the principal hotspot of most LCA analysis published. In general, packaging of canned seafood products has a high contribution on both product's CC and weight, representing, on average, 42% and 27% of the total impact, respectively (Almeida et al., 2021). A main outcome from this study was the contribution in a range of values between 9 and 23% (14% on average) of glass jars packaging to the CC of canned seafood products, which is considerably lower than the only result presented in the review from Almeida et al. (2021), where glass packaging from only one LCA study represented around 40% of the CC of that product (Laso et al., 2017). Glass jars packaging contribution may have likewise some variability, as shown for aluminium and tinplate data in Almeida et al. (2021), but on average the result is less, almost half, when compared with metal cans.

The size of the product should be a feature to consider when improving environmental impacts from packaging. Larger size containers allow for reduction of material impact, a lower amount of packaging materials to be produced, transported and disposed (Ferrara et al., 2023). Glass jars have different sizes and will have higher contribution to a product in a smaller portion. This was the case for product #1 which is half of the size compared with the other three products studied and obtained the highest contribution of packaging in, for example, CC results. As expected from other studies (e.g., Almeida et al., 2021), secondary packaging made of cardboard does not represent a relevant contribution.

Ingredients production cycle phases were highest in CC results for the four products studied. This was expected as production phase is generally the most important phase regarding environmental impacts from food, more than packaging and transport, representing on average around 61% of food's GHG emissions, 79% of acidification, and 95% of eutrophication (Poore and Nemecek, 2018). Nevertheless, differences were identified not only between fish species, but also related to other ingredients as olive oil. Olive oil production contributed significantly to increase results of impact categories related with water (e.g., water use, freshwater eutrophication, and freshwater ecotoxicology). The use of sunflower oil also represented a large contribution to canned albacore tuna for most of the impact categories (e.g., global warming potential, eutrophication potential) in Fernández-Ríos et al. (2022) results. As a result, product #4, which does not include olive or other vegetable oil, but only brine, presented a different outline when compared with the other tuna product. Due to its relative importance, a potential improvement of canned seafood products is to minimize waste of oil during the filling processing, as suggested by Almeida et al. (2015), and to promote its use afterwards, in the consumption phase.

Regarding transport, there is a different case of product #2, in which part of fish is transported from Peru instead of the nearby coast in Portugal or Spain. As a result there was a significant contribution of transport cycle phase, which exceeded the contribution of glass jars in this product. Therefore, transport from distant fish sources might be of relevance to the overall environmental burden of canned seafood products. Considering that the European canning industry is dependent on imported tuna loin products from the Indian Ocean (Miyake et al., 2010) and tuna is the principal product in both Portuguese and Spanish canned seafood industries, transport contribution to canned seafood products produced in Europe might be significant.

The waste generated was not an important contribution to the impact categories selected. However, during the processing phase a significant proportion of fish, around half, corresponding to 49% on average, is converted in by-products. Previous findings reported the same range of values (e.g., Almeida et al. (2015) referred to 49% of total sardine used in canning processing was by-product). Seafood by-products sent to fishmeal production plants can contribute to improve marine resources use efficiency due to their critical role to lower the use of wild fish in aquaculture feed (Naylor et al., 2021).

4.2. Consequences of different packaging end-of-life options for canned products life cycle

If consumers choose to recycle between 2 and 16% GHG emissions would be avoided instead of releasing more emissions as it happened in landfill scenario (between 6 and 10%), the worst EoL choice. Benefits of recycling the glass packaging, i.e. 7.7% reduction of GHG emissions on average, can be a relevant improvement in the carbon footprint of products studied. Therefore, to send glass jars to recycling should be promoted by informing consumers about environmental benefits from glass recycling and its chances of incorporating recycled material in new materials.

To reuse glass jars represented the second highest environmental benefit in terms of GHG emissions and it was above “recycling 50%” of the material, because the remaining 50% goes to landfill and accounts with more emissions. Glass jars were proposed as an environmental improvement for canned seafood products due to its greater potential to be reused several times by consumers prior to the recycling process (Vázquez-Rowe et al., 2014). However, the environmental benefits of reusing glass packaging will depend on the number of uses that can be made prior to the recycling process, in the same way returnable packaging depends on the number of cycles performed (Mata and Costa, 2001). The implementation of a collection system could increase the return rate of glass jars and its number of use cycles, spreading environmental impacts over a longer lifecycle of jars. Nevertheless, it would be also necessary to organize the logistics to receive and wash empty jars together with a system of incentives for consumers. The scenario created included only one more use of glass jars and the outcome would reduce between 5 and 3% the total CC of products #1 and #2, respectively. In the case of products #3 and #4 it would still increase the CC result of the products, between 2 and 3% GHG emissions, respectively, as a consequence of the electricity and water consumption to wash glass jars in a dishwasher, but also due to the fact that packaging had a lower contribution in these two products.

4.3. Comparison of canned seafood with other supply chain products

There are advantages of using canned fish products compared to alternative preservation methods such as chilled and frozen for post-production phases. The results support the hypothesis that when storage at the consumer stage is included, a canned fish product can have lower GHG emissions when compared to frozen alternative stored during some months and represents a significantly longer shelf-life period when compared to chilled preservation mode (i.e., days to years). Frozen scenarios of 3 and 6 months represented more GHG emissions compared with canned fish and compensate the additional emissions coming from packaging (i.e., glass jars production). However, a scenario of 1-month represents the same level of emissions. The chilled fish alternative is a short-term preservation when compared to freezing, canning, salting or drying. Ice can keep the fish fresh and is relatively cheap, nevertheless, chilled fish may generate more food waste at the consumption phase at home due to its short shelf life and handling fragility. The fish waste potential at home was not included in the scenarios created, but 5% of fish waste was added from the fresh supply chain based on James et al. (2011). Vázquez-Rowe et al. (2014) also considered a higher waste ratio for fresh sardines, impairing fried/grilled sardines environmental results when compared with canned option. Canned seafood products have the advantage to be very handy and meet the requirements of a wide range of demographic groups (e.g., from large families with children to people living on their own), avoiding potential waste in the household (Wikström et al., 2014). Their extended shelf life have also the potential to reduce food waste (de la Caba et al., 2019). The avoidance of food waste together with EoL of packaging should be both included in the environmental assessment of these food products (Casson et al., 2022).

Canned products are likewise an interesting option to promote the consumption of small pelagic fish, which have low carbon emissions and achieve high positions in sustainability ratings due to the use of low-impact fishing gears, low number of overfished stocks, and high nutrient density (for 0.25 kg CO_2 eq they provide over 100% of recommended intakes of selenium, vitamins B12 and D, and 69% of omega-3 fatty acids) (Robinson et al., 2022). There is high availability of small pelagic fish species in the EU market linked to catches over time which make these species usually cheaper (EUMOFA, 2022). In Portugal, small pelagic species, as European pilchard and Atlantic chub mackerel, represent the first and second highest landings by weight, contributing with 19% (26,697 tons) and 16% (22,929 tons) for total landings in 2021, respectively (INE, 2022). However, mackerel has an annual apparent consumption per capita in the EU of less than 600 g live weight equivalent per capita, which is considerable less when compared with tuna, with 3.1 kg (EUMOFA, 2022). The EU consumption of tuna is largely supported by imports, which might add extra burden from the transport, but there is also internal production mainly from Spanish and French catches (EUMOFA, 2022). In the case of albacore tuna fishing in Cantabria, it is mostly coastal, with short distances from the ports to the main fishing areas and almost no transport to the processing facilities, resulting consequently in lower GHG emissions than other albacore tuna fisheries around the world (Fernández-Ríos et al., 2022; Parker and Tyedmers, 2015).

5. Conclusions

Seafood plays a key role in healthy diets, while providing food products with relatively low carbon footprints. Environmental assessments vary among species, as well as among processing methods. Canned seafood products allow consumers to easily get access to seafood with high nutritional level, lower environmental impacts, and a long shelf life. Therefore, packaging characteristics, EoL choices, together with food waste potential avoidance, are relevant life cycle phases to be considered when environmental improvements from seafood processed products are investigated.

Glass jars have a lower contribution, on average, to the environmental assessment of canned products when compared with metal cans. Seafood canning industries can adopt a strategy to reduce their products' environmental impacts by increasing the volume of products in glass jars formats, enlarging glass recycled content, encouraging consumers to send their glass jars for recycling, or setting up a collection system for reuse. However, the origin of ingredients, particularly fish, might constitute an important issue when coming from distant sources. Therefore, further LCA studies about different canned seafood products in glass jars are needed to confirm patterns here described.

CRediT authorship contribution statement

Cheila Almeida: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Supervision. **Sandra Ceballos-Santos:** Investigation, Data curation, Writing – review & editing. **Jara Laso:** Investigation, Writing – review & editing. **María Margallo:** Investigation, Writing – review & editing, Funding acquisition. **Rubén Aldaco:** Resources, Funding acquisition. **António Marques:** Resources, Writing – review & editing, Project administration.

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.

Data availability

We shared data as Supplementary material

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Appendix A. Supplementary data

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