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RESEARCH ARTICLE

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Packaging environmental impact on seafood supply chains

A review of life cycle assessment studies

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Abstract

Packaging is fundamental for food preservation and transportation but generates an environmental burden from its production and end-of-life management. This review evaluates packaging contribution to the environmental performance of seafood products. Life cycle assessment (LCA) studies were evaluated by both qualitative and quantitative analysis. The qualitative analysis assessed how direct (e.g., packaging material) and indirect impacts (e.g., influence on seafood loss and waste) have been considered, while the quantitative analysis evaluated packaging contribution to products' weight and climate change impact. Qualitative analysis revealed that seafood LCAs focus mainly on direct environmental impacts arising from packaging materials, for which some articles conducted sensitivity analysis to assess materials substitution. Recycling was found to be the most common recommendation to diminish direct potential environmental impacts arising from packaging end-of-life. However, standardized recovery rates and other end-of-life options (e.g., reuse), should be considered. Quantitative analysis revealed that cans' production contributes significantly to the overall climate change impact for canned products. On average, it contributes to 42% of a product's climate change impact and 27% of a product's weight. Packaging has a lower contribution when considering freezing, chilling, and other post-harvesting processing. It represents on average less than 5% of a product's climate change impact (less than 1 kg CO_2 eq/kg) and 6% of a product's weight. Packaging material production is more relevant to aluminum, tinplate, and glass than for plastic and paper. Therefore, it is essential to accurately include these materials and their associated processes in inventories to improve the environmental assessment of seafood products.

KEYWORDS
canning, fish, food packaging, industrial ecology, life cycle assessment, plastic

1 | INTRODUCTION

Food packaging has the main function of protecting the product from any damage, delivering food in good condition to consumers, and contributing to avoid food loss and waste (FLW) (Russell, 2014). It enables distribution, adds convenience by facilitating accessibility, and can inform about the content, shelf life, and storage (Pauer et al., 2019). The demand for novel food packaging that increase product shelf life and reduce negative environmental impacts of packaging has been growing. However, plastic from packaging is ever more a source of pollution associated to marine litter due to its durability, with reported impacts on several marine species, including fish destined for human consumption (Xanthos & Walker, 2017). In fact, approximately 8.3 million tonnes of plastics reach the ocean on an annual basis, both in the form of microplastics, mainly due to abrasion of tyres and city dust, and macroplastics, due to waste mismanagement (Ryberg et al., 2018). Causes for plastic leakage are attributed to incorrect disposal by consumers but can also be linked to the lack of a proper end-of-life management (Abejón et al., 2020). For instance, the waste-management systems are fairly rudimentary in many developing countries (Vignali, 2016). Given the global food demand, there is likely an enhanced focus on waste mitigation and resource utilization, which will also influence packaging and adjacent industries (Rowan & Galanakis, 2020).

Consumers are generally exposed only to packaging at the retailing and waste stages of the supply chain (Russell, 2014). However, packaging cannot be separated from the product chain and its different packaging levels (Denham et al., 2015). The first level, primary packaging, refers to the packaging in direct contact with the product (e.g., aluminum can), while secondary packaging corresponds to subsequent layers of material that contain one or more primary packaging (e.g., cardboard box), and tertiary packaging is designed for the purposes of transport, handling, and/or distribution and typically is not seen by consumers (e.g., pallets) (ISO, 2016). The production, use, and disposal of packaging are associated with a multitude of potential environmental impacts (Flanigan et al., 2013). Direct environmental impacts are the effects occurring during the production, transport, or recycling of packaging materials (e.g., metal, paper, glass, plastic) (Lindh et al., 2016), while indirect environmental impacts come from the influence of packaging on the food product's life cycle (e.g., the effect of packaging on reducing FLW or on transport efficiency) (Molina-Besch et al., 2019). The environmental burden from FLW often exceeds that of packaging, and a FLW increase corresponds to a higher environmental cost of the product coming from all the resources devoted to production that were wasted (Wikström et al., 2014). Packaging can be even more relevant to seafood since it is highly prone to spoilage in comparison to other food (Love et al., 2015). It is estimated that 36% of the total edible seafood is lost or wasted in Europe throughout the supply chain, between landing and consumption (Gustavsson et al., 2011).

Life cycle assessment (LCA) is a methodology that evaluates the potential environmental impacts associated with a product by inventorying and evaluating inputs (energy and raw materials) and outputs (emissions to air, water, and soil) over the product's life cycle (Del Borghi et al., 2020). LCA studies on food have shown that later stages in the supply, such as packaging, retail, and transport, all combined contribute to less than 14% to climate change impact (Poore & Nemecek, 2018). However, packaging can contribute significantly to climate change impacts of certain products (e.g., canning), when packaging production is the major hotspot due to high energy needs for materials' production (Poovarodom et al., 2012). On the other hand, packaging can also represent an opportunity to reduce impacts from food by avoiding food waste (Heller et al., 2019). At the consumption stage, 20–25% of household food waste can be related to packaging design attributes (Williams et al., 2012).

The number of LCA studies related to seafood has risen considerably in the 2000s, with several studies assessing the impact of different seafood products (Avadí et al., 2020; Bohnes et al., 2019). Yet, seafood is a complex sector consisting of many species caught by different fishing gears (Parker et al., 2018; Parker & Tyedmers, 2015) or reared in a variety of aquaculture systems and environments (MacLeod et al., 2020). Most seafood LCA studies, either from fisheries or aquaculture, focused on the production stage, overlooking packaging and processing stages contribution. Fish preparation for fresh consumption undergoes basic processing tasks (i.e., cleaning, gutting), but processing methods such as canning, curing (salting-curing), or freezing require further operations (Vázquez-Rowe, Villanueva-Rey, et al., 2012). Studies that covered the whole seafood chain showed that packaging contribute to less than 15% to the climate change for frozen, chilled, and cooked seafood products (V. Putten et al., 2015;

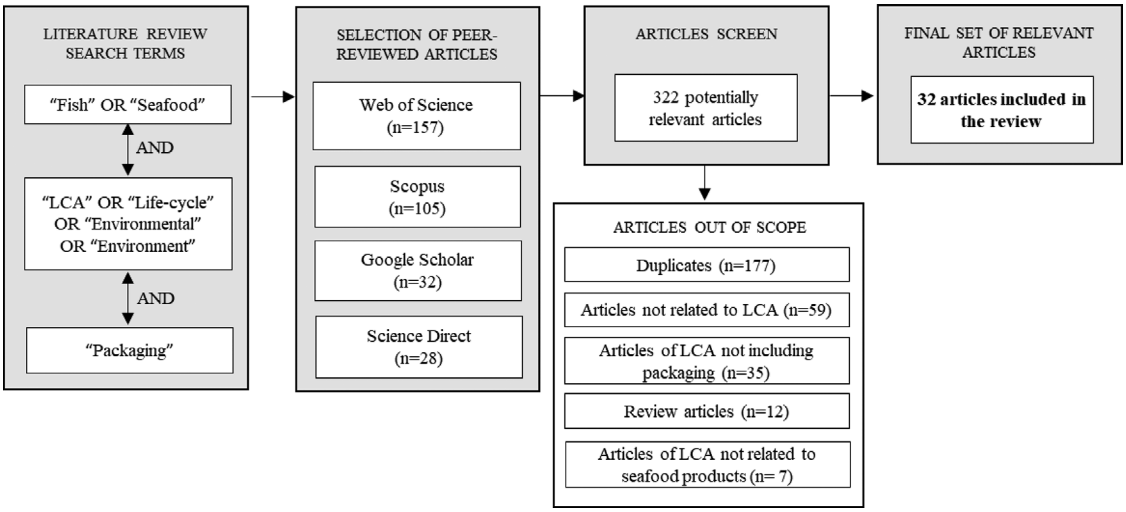

FIGURE 1 Flow diagram of the literature review

Svanes et al., 2011b; Vázquez-Rowe et al., 2011). However, in the case of canned seafood packaging can contribute significantly to the product's climate change impact, where the production of packaging (tinplate and aluminum) can be the major hotspot (Avadí et al., 2014; Iribarren, Hospido, et al., 2010; Vázquez-Rowe et al., 2014). Important environmental savings may be achieved by optimizing packaging of seafood products (Almeida et al., 2015; Avadí et al., 2014; Pardo & Zufía, 2012). Nevertheless, more empirical data on food packaging, covering different information requirements, including material, weight, shape, and end-of-life phase, is needed (Molina-Besch, 2016; Molina-Besch et al., 2019).

Consequently, this timely review used seafood LCA-published studies in order to evaluate features and find patterns related to packaging environmental assessment. The aim was to make a systematic review of packaging included in seafood products LCAs. For this purpose, two distinct analyses were performed: (a) qualitative, to evaluate how packaging direct and indirect environmental impacts have been addressed; and (b) quantitative, to evaluate packaging contribution (weight and climate change impact) on seafood products' life cycle; together with a discussion on main challenges to improve seafood packaging sustainability identified.

2 | METHODS

2.1 | Literature search strategy and inclusion criteria

The review was carried out by conducting searches for studies published in peer-reviewed indexed journals in electronic databases (Web of Science, Scopus, Google Scholar and Science Direct), in the last 20 years (from January 2000 to December 2019). The combined search terms "fish" or "seafood," "LCA" or "life-cycle" or "environmental" or "environment," and "packaging," on titles, abstracts, and keywords, were considered as presented in Figure 1. Opinions, conference articles, and grey literature were not included, and only full-length articles in English published in a peer-reviewed journal were selected.

The literature search resulted in a total of 322 potentially relevant articles. A refinement was made by removing duplicates (177 articles) and excluding studies with the following criteria: if not directly related to LCA or not presenting an LCA case study (59 articles); if not including packaging in the scope (35 articles); if being a review article and not having detailed information about products packaging like case studies (12 articles); and if not related to seafood products (7 articles). Cumulatively, this search resulted in the selection of 32 seafood LCA case studies including packaging.

2.2 | Analysis of LCA articles focusing on packaging

The products identified in each article were categorized by species, production type (fishery or aquaculture), post-harvest processing (canning, chilling, freezing, or others), primary and other packaging levels materials, and geographic scope. Besides, methodological choices from each article were also identified, in particular, functional unit, system boundaries, allocation method, life cycle impact assessment (LCIA) method, and impact categories used. All categorized information extracted from the articles is included in Table S1 in the Supporting Information. A list of seafood products found in the 32 articles was obtained and packaging contribution to each product, based on quantitative data from weight and climate change impact figures, and qualitative data on inclusion of environmental impacts of packaging in life cycle steps, were collected and analyzed.

2.2.1 | Qualitative analysis

A qualitative analysis discussing direct and indirect environmental impacts of packaging in the LCA studies selected was performed following the analytical framework developed by Molina-Besch et al. (2019). This framework evaluates the inclusion of direct and indirect environmental impacts of packaging in each product's life cycle step, the development of sensitivity analysis to investigate how the results would change if conditions were different, and the proposal of recommendations. The following life cycle steps were considered: (1) primary packaging material (direct impact); (2) secondary packaging material (direct impact); (3) FLW (indirect impact); (4) seafood transport from producer to retail (indirect impact); (5) energy consumption of seafood storage (indirect impact); (6) seafood preparation by households (indirect impact); (7) packaging end-of-life (direct impact), and; (8) emerging innovations (indirect impact).

The direct environmental impacts coming from packaging material and its end-of-life come mainly from material production and its waste-management process, respectively, and may involve different operations. In the other life cycle steps, where indirect impacts were considered, evaluation of the influence of packaging to FLW avoidance, energy consumed in storage, preparation method by households and, innovations proposed to the products, was performed. Therefore, to each life cycle step, the inclusion (Yes/No) of: (1) packaging in the scope of the LCA study; (2) sensitivity analysis; and (3) recommendations, was evaluated. Besides, specific recommendations on measures to improve packaging were identified and described.

2.2.2 | Quantitative analysis

In order to perform a quantitative analysis, life cycle inventory (LCI) data and LCIA results from the selected articles were collected. When available, quantifiable packaging data related to its weight from LCI data and the LCIA results for the climate change impact category were retrieved from the articles. When these data were not available in the articles, it was directly requested to authors. It should be noted that system boundaries, assumptions, and background LCI databases are not the same in all articles. For example, post-harvest stages to all products include at least a cradle-to-gate assessment, but some articles also included retailing (cradle-to-market) or end-of-life of packaging (cradle-to-grave). Therefore, this quantitative analysis does not compare results between different products but rather provides a range of results typically found in the literature. The data were compared between different type of post-harvest processing—canning, freezing, chilling, and others (e.g., cooking), or main packaging material—aluminum, tinplate, plastic, paper, wood, and glass.

The data obtained were gathered from 27 articles of the 32 selected. Five articles were excluded from this analysis because their data set was identical to data presented in other articles included in the analysis (Iribarren, Moreira, et al., 2010b; Svanes et al., 2011b; Vázquez-Rowe, Villanueva-Rey, Moreira, et al., 2013) or it was not possible to reach any quantitative data for packaging (Mungkung et al., 2006; Nhu et al., 2015). The list of articles and data retrieved is synthetized in Table S2 in the Supporting Information.

The LCI data collected were investigated to quantify weight contribution of packaging to the final product weight (Cw_{pack}, %) (Equation 1):

$$Cw_{pack} = \frac{w_{pack}}{w_{pack} + w_{food}}, \quad (1)$$

where, w_{pack} is the packaging weight (kg) and w_{food} is the food packaged weight (kg). Packaging weight includes both primary and secondary packaging. Food weight includes both seafood and other ingredients (e.g., olive oil or other sauce type).

For LCIA, the climate change impact category was selected because all articles included this impact category and impacts are based on characterization factors from the Intergovernmental Panel on Climate Change (IPCC). Only environmental impacts related to greenhouse gas (GHG) emissions were covered in this analysis, but trade-offs related to other impact categories exist and should be considered to make further decisions. By quantifying emissions specifically from seafood products, the results can contribute to monitor product's impacts and improve how food's environmental impacts are managed and communicated to limit climate change (Poore & Nemecek, 2018). Therefore, LCIA results were investigated to quantify climate change contribution of the packaging (Ccc_{pack}, %) to the total climate change impact considered. The Ccc_{pack} was obtained either by collecting directly the contribution from the article or by using Equation (2):

$$Ccc_{pack} = \frac{cc_{pack}}{cc_{total}} \quad (2)$$

where, cc_{pack} is the packaging climate change impacts (kg CO_2 eq) and CC_{total} is the total climate change impacts over the product life cycle (kg CO_2 eq). It should be noted that when the LCIA data received from authors was that the cc_{pack} contribution was very small, a contribution of 0.5% was considered for the analysis. This was the case of three products: chilled salmon (Parker, 2018) and chilled and frozen mussels (Iribarren, Moreira, et al., 2010c).

3 | RESULTS AND DISCUSSION

The main information arising from seafood LCA studies selected from the literature review are presented in Table 1. In cases where a single study yielded several products, these were considered to be separate products if representing different species or were produced from different processing methods. Therefore, from the 32 articles selected, a total of 50 products were retrieved for analysis. A higher number of articles selected presented products from fisheries ($n = 21$) compared to aquaculture ($n = 10$), and one study does not specify the production source.

The products analyzed comprise 24 species, but more species could be included since some studies only mention the species group that may correspond to more than one species (e.g., tuna). The species were then organized in 15 species groups (Table 1), including fish (anchovy, catfish, cod, hake, salmon, sardine, tilapia, trout, and tuna), crustaceans (lobster, shrimp, and prawn), cephalopods (octopus), and bivalves (mussels and oysters).

According to post-harvest processing information, canned seafood studies ($n = 17$) present a small variety of products, including anchovies, mussels, sardines, and tuna. Chilled products ($n = 12$) are associated with hake, lobsters, oysters, trout, and salmon, while frozen products ($n = 17$) are linked with cod, hake, octopus, prawns, shrimps, tilapia, and shrimps. The category "Others" ($n = 4$), related to processing operations like cooking and a combination of freezing and modified atmosphere packaging (MAP), or chilled and pasteurized, presented products with tuna, lobsters, catfish, and other fish species not specified.

Two main primary packaging materials—tinplate and aluminum—were associated to canned seafood products, although other types of packaging are considered (e.g., plastic from a retort pouch and glass). Chilled products were associated with primary packaging made of paper, plastic, and one with wood used for oysters, while frozen products were only linked with paper and plastic. The category "Others" included only plastic materials. All products analyzed included primary packaging, but 22 out of the 50 products evaluated presented information related to secondary packaging. Secondary packaging consisted usually of cardboard boxes, but plastic films, expanded polystyrene boxes, and pallets were also considered. More than half of the articles have the geographical scope in Europe (56%); the remaining are related to other five main continents left. Data related to geographic scope, system boundaries, and LCIA methods can be accessed in Table S1 in the Supporting Information.

The articles used different LCIA methods, but CML, a midpoint-oriented method (Heijungs et al., 1992), is the most used method. It is followed by ReCiPe, a method that comprises harmonized category indicators at the midpoint and endpoint level (Goedkoop et al., 2013). Midpoint indicators characterize impact mechanisms in the cause–effect chain (such as climate change, toxicity, or eutrophication) whereas endpoint indicators characterize final damage from midpoint impacts to three areas of protection (human health, ecosystem quality, and resource scarcity). Likewise, the functional units are based on different measurements as weight of the whole product, only edible product (Almeida et al., 2015), or protein quantity (Vázquez-Rowe et al., 2014). Therefore, the impact assessment results are not comparable in absolute terms, but they are useful for further examining patterns on the environmental assessment of packaging on seafood products, both for qualitative and quantitative analysis.

3.1 | Qualitative analysis of packaging in seafood LCA studies

Table 2 summarizes results of the packaging qualitative analysis. Overall, it was found that packaging was seldom included in the life cycle steps analyzed and is considered more in direct than indirect impacts, that is, primary packaging material (100% of articles), secondary packaging material (44% of articles), and packaging end-of-life (31% of articles). For the five indirect impacts considered, packaging was considered in 34% for preparation by households, 13% for both transport from producer to retail and storage, 3% for emerging innovations, and not considered for FLW. Sensitivity analyses were carried out only for the primary packaging material (direct impact) in 7 out of 32 articles, and in one article for the transport from producer to retail life cycle step (indirect impact). Recommendations were found for all life cycle steps, except storage and preparation by households.

Primary packaging material was the life cycle step that presented the highest number of sensitivity analysis (22% of articles) and recommendations (38% of articles). Most of the recommendations were related to the substitution of packaging material for canning and curing products ($n = 8$), as the use plastic or glass instead of tinplate or aluminum. Replacing tinplate by aluminum, as proposed by Avadí et al. (2015) for canned tuna would reduce the environmental impact by 63% at the endpoint level for the three areas of protection (human health, resources, and ecosystems) (ReCiPe method). In the case of canned sardine products, the same replacement was proposed by Almeida et al. (2015) and led to a reduction of 56% of the climate change. Hospido et al. (2006) suggested that the use of plastic bags instead of tinplate cans for tuna packaging would represent a reduction up to 50% in terms of climate change and acidification for the overall assessment of the product. Likewise, according to Almeida et al. (2015) and Laso et al. (2018), plastic seems to be the best option because it shows the lowest values for all the impact categories studied. Apart from the use of plastic formats, Vázquez-Rowe et al. (2014) proposed glass jars, which have a greater potential depending on the number of times the glass is reused by consumers prior to the recycling process. However, these recommendations raise the argument that packaging material substitution implies a change in the product final appearance, which may affect consumers' acceptance (Hospido et al., 2006; Laso et al., 2017), and considerable changes in machinery linked to industrial logistics. Other recommendations for primary packaging were related to changing packaging design ($n = 3$), namely

TABLE 1 Main information of the seafood LCA studies selected

#	Reference	Species group	Production type	Functional unit	Post-harvest processing	Primary packaging*	Other packaging*
1	Almeida et al., 2015	Sardine	Fisheries	1 kg of edible canned sardines in olive oil	Canning	Aluminum can	Corrugated board
2	Avadí et al., 2014	Anchovy	Fisheries	1 kg of fish product	Canning	Tinplate can	–
					Canning (curing)	Tinplate and aluminum can	
3	Avadí et al., 2015	Tuna	Fisheries	1 t of tuna product	Canning	Tinplate can	–
					Canning (pouch)	Retort pouch (plastic)	
					Freezing (vacuum bagged)	Thermo-shrinkable bag (plastic)	
4	Driscoll et al., 2015	Lobster	Fisheries	1 t of live lobster	Chilling	Corrugated cardboard, polystyrene, and cotton fiber	–
5	Farmery et al., 2014	Lobster	Fisheries	1 kg of live lobster	Chilling	Polystyrene boxes with wood wool, ice packs	–
6	Farmery et al., 2015	Prawn	Fisheries	1 kg of frozen banana prawn	Freezing	Cardboard box	–
7	Hospido et al., 2006	Tuna	Fisheries	1 t of raw tuna entering the factory	Canning	Tinplate can	Cardboard box, plastic film
8	Iribarren, Hospido, et al., 2010	Mussels	Aquaculture	Triple pack of round can of mussels	Canning	Tinplate can	Cardboard
9	Iribarren, Moreira, et al., 2010	Mussels	Aquaculture	65 t of CaCO3 products and 278 t of mussel pâté	Canning	Tinplate can	Cardboard, packaging film
10	Iribarren, Moreira, et al., 2010b	Mussels	Aquaculture	1 kg of mussels product	Canning	Tinplate can	Cardboard, LDPE bag
					Chilling	Mesh bag of HDPE	
11	Iribarren, Moreira, et al., 2010c	Mussels	Aquaculture	35 kg of canned mussels	Canning	Tinplate can	Cardboard (can) and LDPE bag
				40 kg of fresh mussels	Chilling	Mesh bag of HDPE	LDPE bag
				20 kg of frozen mussels	Freezing	Paperboard and plastic	LDPE bag
12	Laso et al., 2017	Anchovy	Fisheries	1 kg of raw anchovy entering the factory	Canning	Aluminum can	Cardboard boxes, LDPE film
						Tinplate can	
						Glass jar	
						Plastic packaging	
13	Laso et al., 2018	Anchovy	Fisheries	1 kg of fresh European anchovy entering the factory	Canning	Aluminum can with cardboard box	Corrugated and cardboard boxes, LDPE film
					Canning (curing)	Aluminum can with cardboard box	Corrugated cardboard boxes, LDPE film

(Continues)

TABLE 1 (Continued)

#	Reference	Species group	Production type	Functional unit	Post-harvest processing	Primary packaging*	Other packaging*
14	Mungkung et al., 2006	Shrimp	Aquaculture	1.8 kg of frozen shrimp	Freezing	Material not specified	—
15	Nhu et al., 2015	Catfish	Aquaculture	1 t of Pangasius fillets leaving the factory	Other (freezing and modified atmosphere packaging)	Polyethylene and cardboard	—
16	Pardo and Zufía, 2012	Fish (sp not identified)	Not specified	1 kg of the pre-cooked dish of fish and vegetables	Other (cooking)	Polypropylene	—
17	Parker, 2018	Salmon	Aquaculture	1 kg of head-on gutted salmon	Chilling	Polyethylene lined polystyrene boxes	—
18	Pelletier and Tyedmers, 2010	Tilapia	Aquaculture	1 t of tilapia	Freezing	Cardboard and plastic	—
19	Silvenius et al., 2017	Trout	Aquaculture	1 t of skinless fillet of fish	Chilling	Plastic	—
20	Svanes et al., 2011	Cod	Fisheries	1 kg of cod wetpack	Freezing	Polyamide and polyethylene	Polyethylene film, wood pallet, carton
				1 kg of frozen cod	Freezing	Polyamide and polyethylene	Corrugated board, wood pallet
				1 kg of fish burger	Freezing	LDPE and corrugated board	LDPE, wood pallet
				1 kg of loins	Chilling	HDPE tray and plastic film	Expanded polystyrene, LDPE film
21	Svanes et al., 2011b	Cod	Fisheries	1 kg wetpack	Freezing	Polyamide and polyethylene	Polyethylene film, wood pallet, carton
				1 kg fish burger	Chilling	LDPE and corrugated board	LDPE, wood pallet
				1 kg loins	Freezing	HDPE tray and plastic film	Expanded polystyrene, LDPE film
22	Tamburini et al., 2019	Oysters	Aquaculture	1 kg of commercial fresh oysters at farm gate	Chilling	Wooden baskets	—
23	van Putten et al., 2016	Lobster	Fisheries	1 kg live southern rock lobster	Chilling	Styrofoam boxes	—
				1 kg live tropical rock lobsters	Chilling	Styrofoam boxes	
				350 g tropical rock lobster	Freezing	Waxed cardboard box	

(Continues)

TABLE 1 (Continued)

#	Reference	Species group	Production type	Functional unit	Post-harvest processing	Primary packaging*	Other packaging*
24	Vázquez-Rowe et al., 2011	Hake	Fisheries	500 g of raw gutted fresh hake fillet at the household	Chilling	HDPE	Polystyrene, fish boxes
25	Vázquez-Rowe, Moreira, et al., 2012	Octopus	Fisheries	24 kg cartoon of frozen octopus	Freezing	Corrugated board and polyethylene	Pallets
26	Vázquez-Rowe et al., 2013	Hake	Fisheries	324 g of sticks	Freezing	Cardboard box, polyethylene, and retractable polyolefin	—
27	Vázquez-Rowe, Villanueva-Rey, Moreira, et al., 2013	Hake	Fisheries	324 g of frozen fish sticks of Patagonian grenadier	Freezing	Cardboard and polyethylene boxes	—
28	Vázquez-Rowe et al., 2014	Sardines	Fisheries	85 g of protein supplied by one can of sardines in olive oil	Canning	Tinplate can	Cardboard, Corrugated board, plastic film
29	Ziegler and Valentinsson, 2008	Lobster	Fisheries	300 g of Norway lobster tails	Other (cooking)	Disposable bucket of polypropylene	—
30	Ziegler et al., 2003	Cod	Fisheries	400 g frozen cod fillets	Freezing	LDPE and laminated cardboard	LDPE
31	Ziegler et al., 2011	Shrimp	Fisheries	1 kg of shrimp and packaging material at the point of import to Europe	Freezing, industrial Freezing, artisanal	Cardboard Cardboard	—
32	Zufia and Arana, 2008	Tuna	Fisheries	2 kg tray of pasteurized tuna with tomato	Other (cooking - pasteurizing)	Vacuum-packaged made of HDPE, polyethylene film, and polyamide nylon	—

*Packaging materials: LDPE, low density polyethylene; HDPE, high density polyethylene.

TABLE 2 Results of the qualitative analysis related to the packaging environmental impacts, including packaging recommendations for improving the environmental performance of packaging identified in seafood LCA-reviewed articles

Life cycle step	Packaging included in the scope of LCA studies	Sensitivity analysis in LCA studies	Recommendations in LCA studies	Type of recommendation (# –article number in Table 1)
Primary packaging material (direct impact)	100% (*n* = 32)	22% (*n* = 7)	38% (*n* = 12)	▪ Substitution of tinplate or aluminum by other packaging non-metal materials such as plastic or glass for canned products (articles #1, #3, #7, #8, #12, #13, #28) ▪ Substitution of tinplate or aluminum by glass container for cured products (article #2) ▪ Use larger cans for canning products (articles #2, #3) ▪ Redesign of the package with regard to form and composition for pre-cooked products (article #32) ▪ Substitution of plastic boxes with laminated cardboard to transport frozen products (article #21) ▪ Reduce weight in the primary package (articles #15, #16)
Secondary packaging material (direct impact)	44% (*n* = 14)	0% (*n* = 0)	3% (*n* = 1)	Modify secondary packaging to reduce the impact related to food preservation methods (article #16)
Food loss and waste (indirect)	0% (*n* = 0)	0% (*n* = 0)	6% (*n* = 2)	▪ Canned products can lower the risk of food losses (article #1) ▪ Higher data quality regarding food waste in post-landing activities is needed (article #28)
Transport from producer to retail (indirect impact)	13% (*n* = 4)	3% (*n* = 1)	3% (*n* = 1)	Substitution of boxes material to transport frozen products with less weight (article #21).
Storage (indirect impact)	13% (*n* = 4)	0% (*n* = 0)	0% (*n* = 0)	–
Preparation by households (indirect impact)	34% (*n* = 11)	0% (*n* = 0)	0% (*n* = 0)	–
Packaging end-of-life (direct impact)	31% (*n* = 10)	0% (*n* = 0)	9% (*n* = 3)	▪ Avoid packaging waste because recycling/reuse of packaging materials reduces burden via substitution of virgin materials (articles #15, #16) ▪ Each additional unit of material recycled would displace an equivalent quantity of the current mix of virgin (article #12)
Emergent innovations (indirect impact)	3% (*n* = 1)	0% (*n* = 0)	3% (*n* = 1)	The application of different preservation technologies and development of novel products imply the selection of different packaging and it must be carefully considered since the type of packaging may play an important role when aiming to improve sustainability of food preservation methods (article #16)

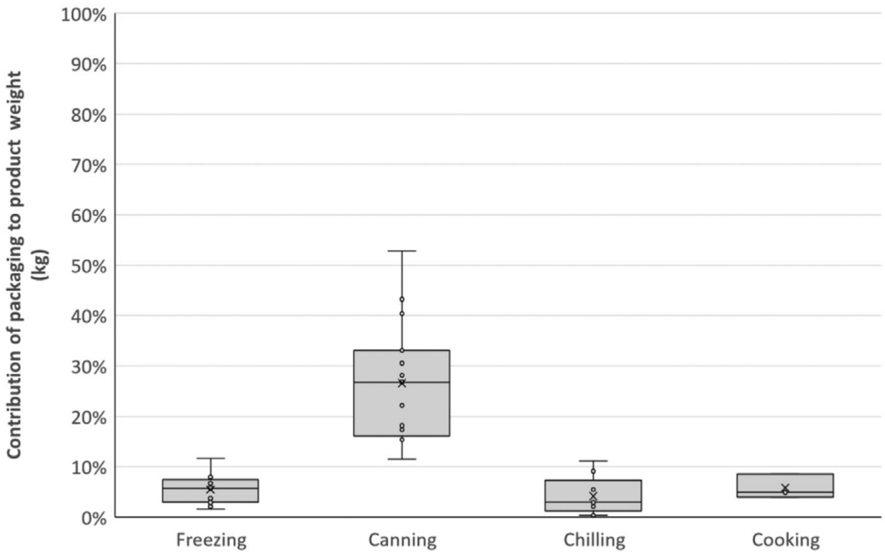

FIGURE 2 Contribution of packaging to the final weight of the seafood products by post-harvest processing. The underlying data for this figure can be found in the Supporting Information

the size by using larger cans for canned products (Avadí et al., 2014, 2015), or form by redesigning the package (Zufia & Arana, 2008). Two articles also recommended to reduce the amount and consequently the weight of the material used in the package (Nhu et al., 2015; Pardo & Zufía, 2012).

The inclusion of the secondary packaging material was found in 44% of the articles analyzed, but only one issued a recommendation specifically related to this type of packaging. Pardo and Zufía (2012) suggested the modification of both primary and secondary packaging as the best opportunity to reduce the impact assessment of the final product within different food preservation technologies.

Packaging was not associated with FLW among the 32 articles analyzed, but two recommendations were found. One article asked for higher data quality regarding food losses in post-landing activities where packaging has a role (Vázquez-Rowe et al., 2014), and the other pointed out that canning has a post-harvesting process that contributes to lower the risk of food losses along the supply chain, in part due to its long shelf life related to packaging preservation features (Almeida et al., 2015).

Packaging was considered both in the transport and storage stages in 13% of the articles analyzed, but recommendations were found only to transport and in one article. Svanes et al. (2011b) suggested the substitution of plastic boxes with laminated cardboard to transport frozen products to alleviate the weight carried. The effect of such a replacement could represent a reduction of 0.7–1.1% of total climate change of the seafood product.

Preparation by households is the life cycle step from indirect environmental impacts where packaging was most considered, being found in 34% of articles analyzed. However, no recommendations to decrease this indirect impact have been found in the literature.

The end-of-life step included packaging in the environmental impact in 31% of the articles. Recommendations found in three articles denoted the importance of recycling packaging materials to reduce the burden via substitution of virgin materials. However, recycling is considered in different ways depending on the article, thus introducing variability to results. For instance, in the case of the anchovy it was assumed that 37% of aluminum cans and 84% of cardboard boxes were recycled (Laso et al., 2018), while in the case of mussels it was 64% of tinplate cans and 62% of cardboards and the rest is disposed as general waste (Iribarren, Moreira, et al., 2010b).

Emerging innovations and its relation to packaging have been poorly explored in seafood LCA studies. Only Pardo and Zufía (2012) mentioned that application of different preservation technologies and development of novel products imply also the selection of different packaging options. However, innovations must be carefully considered, especially when the aim is to improve the sustainability of the preservation method, since the type of packaging may play an important role.

3.2 | Quantitative analysis of packaging in seafood LCA studies

The contribution of packaging to the final weight of seafood products was assessed according to the type of post-harvest processing (Figure 2) and main packaging material (Figure 3). For frozen, chilled, and pre-cooked products, packaging has a relatively low contribution to weight, representing less than 6% and ranging between 0% and 12%. Yet, for canned products, the weight importance of packaging represents on average 27% seafood product weight, ranging between 11% and 53%. The high variability obtained comes principally from differences between metal and glass materials.

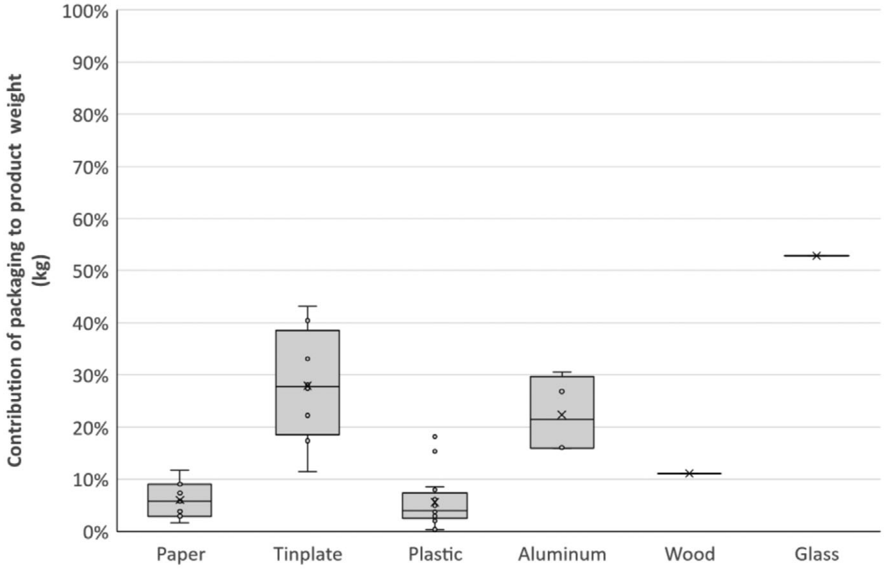

FIGURE 3 Contribution of packaging to the final weight of the seafood products by main packaging material. The underlying data for this figure can be found in the Supporting Information

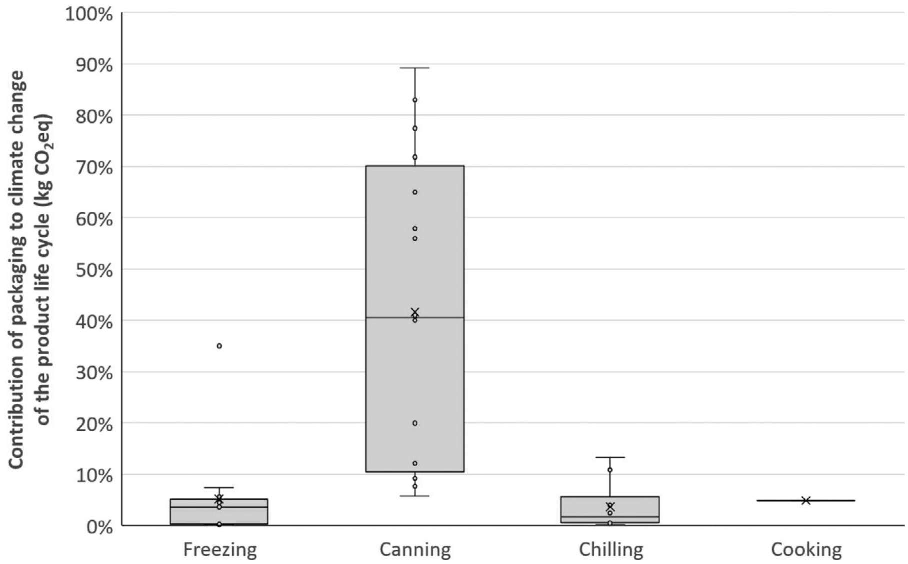

FIGURE 4 Contribution of packaging to climate change impact in the life cycle of seafood products by type of post-harvesting processing. The underlying data for this figure can be found in the Supporting Information

Glass is the packaging material with the highest contribution to the product weight, even if found in only one product with 53% contribution (Laso et al., 2017). It is followed by tinplate, and aluminum, with 28% and 22% on average, respectively. Packaging made by plastic and paper presented the lowest contribution to the product weight, with 6% on average. Wood represented around 11% of product weight, but it was included only in one article. Information on package size or volume was not accessible and it was not possible to confirm if smaller package sizes led to a higher packaging contribution than larger ones. However, the weight gives the specific amount of each material used in the package.

The relative contribution of packaging to climate change impact in the life cycle of seafood products was analyzed according to the type of post-harvesting operations (Figure 4) and packaging main material (Figure 5). For canned products, packaging contribution to climate change impact is significant, representing on average 42% of the product life cycle and ranging between 6% and 89%. Canning packaging usually results in more than 1 kg CO_2 eq/kg of food (Table 3). Among the canning packaging materials, both tinplate and aluminum, presented almost the same order of contribution, ranging between 6–89% and 10–83%, respectively, explained by the high environmental impacts associated with energy requirements for extraction, processing, and transport of these materials (Vázquez-Rowe et al., 2014). The high variability found in the contribution of packaging to the overall impacts of canning products might be explained by three main reasons. First, the high contribution of packaging to the product's

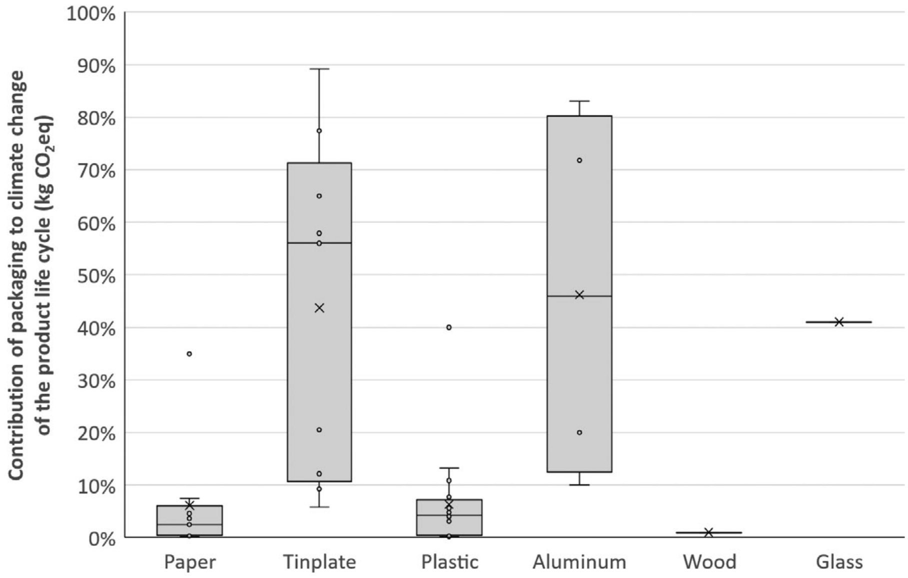

FIGURE 5 Contribution of packaging to climate change impact in the life cycle of seafood products by packaging main material. The underlying data for this figure can be found in the Supporting Information

weight, as explained above. Second, the impact from seafood production, resulting in different relative contributions from packaging. For instance, climate change impact for sardine from Portuguese purse seiners was almost half of that from Galicia (Almeida et al., 2015). Third, can production includes different operations and its associated background data might be modeled in different ways, considering different sources or assuming country-specific recycling rates of materials. For instance, sealing compounds, coatings, or substances used in the inner cans are difficult to consider or are not included in the articles (e.g., Avadí et al., 2014). Furthermore, metal cans are modeled from metal sheets and a margin for scraps production and metalwork is necessary to be included, challenging the ecoinvent paradigm of modeling all products in bulk (Avadí et al., 2020). To overcome such variability further experimental research is required to optimize the environmental impact on canned processing and to confirm to which extent the factors here identified affect the LCA results.

Packaging contribution from freezing, chilling, and other types of seafood products' processing is on average less than 5% of climate change impact for the seafood life cycle, and usually results in less than 1 kg CO_2 eq/kg of food (Table S2 in the Supporting Information). Regarding the type of materials used in the packaging, a major difference among paper, plastic, or wood was not observed. However, packaging of one frozen product made of paper represented around 35% of climate change impact. It corresponds to 1 kg of shrimp caught by an artisanal fishery (Ziegler et al., 2011), which is associated to a low climate change impact production method (8 kg CO_2 eq/kg of food) and, as a consequence, the packaging relative contribution was enlarged.

Most proposals for seafood LCA improvements are mainly focused on reducing energy or fuel consumption. However, for the canning industry, even though the thermal processes of cooking and sterilization are an important part of the process, results showed that can production is the most important contributor to climate change impact. Several authors reported the environmental impacts of packaging in canned seafood products, such as tuna (Avadí et al., 2015; Hospido et al., 2006), sardine (Almeida et al., 2015; Vázquez-Rowe et al., 2014), mussels (Iribarren, Hospido, et al., 2010; Iribarren, Moreira, et al., 2010a), and anchovy (Avadí et al., 2014; Laso et al., 2018). Tinplate was the most common material described in the selected articles for canning products, whereas aluminum was only identified for canned Portuguese sardine (Almeida et al., 2015) and Cantabrian anchovy (Laso et al., 2018). Other options such as glass and plastic were included in only one article (Laso et al., 2017) and further LCA studies with foreground data related to these packaging materials are needed to confirm patterns here described.

Regarding frozen products, cardboard combined with plastics have been widely applied for primary packaging. For cooked products, the final preparation has a high influence on the packaging choice, since some products are microwaved and require plastic packaging. Nevertheless, due to the low contribution from these materials (paper and plastic), the efforts to reduce environmental impacts from packaging of frozen and cooked seafood products should be more focused on indirect impacts, such as increasing the potential to reduce seafood loss and waste.

3.3 | Main challenges to improve seafood packaging sustainability—Food waste, circular economy, and innovation

Food waste is highly influenced by primary packaging design, its materials, and date labeling schemes (de la Caba et al., 2019; Heller et al., 2019). For example, packaging design influences FLW if the packaging is not easy to empty and food remains attached to the packaging surface

TABLE 3 Results of the quantitate analysis of the packaging contribution to products' weight and climate change (CC) of the product life cycle

#	Type*	Packaging material	Packaging weight (kg)	Product weight including packaging (kg)	Contribution of packaging to product weight (%)	CC for FU (kg CO_2 eq/kg of food)	CC of packaging (kg CO_2 eq/kg of food)	Contribution of packaging to CC of product life cycle (%)
1	CA	Aluminum	0.4	1.4	30.6	7.7	5.5	71.8
2.1	CA	Tinplate	0.1	1.1	11.5	1.9	1.2	65.0
2.2	CA	Tinplate	0.2	1.2	17.4	3.7	2.1	57.9
3.1	CA	Tinplate	10,590,814.0	31,982,814.0	33.1	8.0	1.6	20.5
3.2	CA	Plastic	561,667.6	3,091,667.6	18.2	4.1	0.3	7.7
3.3	F	Plastic	206,552.0	3,074,552.0	6.7	3.8	0.0	0.2
4	CH	Paper	100.0	1100.0	9.1	–	0.2	2.5
5	CH	Plastic	0.0	1.0	2.9	31.0	1.0	3.1
6	F	Paper	0.0	1.0	2.9	7.2	0.1	0.7
7	CA	Tinplate	447.4	1107.4	40.4	8.3	1.0	12.1
8	CA	Tinplate	93.7	342.7	27.3	17.8	15.9	89.2
9	CA	Tinplate	108.7	386.5	28.1	1.8	0.2	9.2
11.1	CA	Tinplate	0.8	1.8	43.2	9.8	0.6	5.8
11.2	CH	Plastic	3.8	1003.8	0.4	13.9	–	0.5
11.3	F	Paper	0.1	1.1	5.7	9.5	–	0.5
12.1	CA	Aluminum	0.1	0.7	16.1	–	–	83.0
12.2	CA	Tinplate	0.2	0.8	22.2	–	–	56.0
12.3	CA	Glass	0.7	1.3	52.8	–	–	41.0
12.4	CA	Plastic	0.1	0.7	15.4	–	–	40.0
13.1	CA	Aluminum	118.3	743.3	15.9	–	–	10.0
13.2	CA	Aluminum	299.5	1116.5	26.8	–	–	20.0
16	CO	Plastic	51.5	1051.5	4.9	–	0.1	–
17	CH	Plastic	0.0	1.0	2.1	13.2	–	0.5
18	F	Paper	132.5	1132.5	11.7	2.0	0.1	3.7
19	CH	Plastic	–	–	–	5.4	0.0	13.2
20.1	F	Plastic	0.0	0.4	3.7	3.6	0.2	4.5
20.2	F	Plastic	0.0	0.4	7.9	3.7	0.2	4.8
20.3	F	Plastic	0.3	5.3	6.1	1.8	0.1	5.6
20.4	CH	Plastic	0.1	2.1	5.4	7.6	0.3	4.0
22	CH	Wood	0.1	1.1	11.1	1.9	0.0	1.0
23.1	CH	Plastic	0.0	1.0	2.9	15.8	0.2	1.0
23.2	CH	Plastic	0.0	1.0	2.9	9.3	0.0	0.2
23.3	F	Paper	0.0	0.4	3.8	3.2	0.0	0.2
24	CH	Plastic	1.5	501.5	0.3	3.8	0.8	10.9
25	F	Paper	393.8	24,393.8	1.6	7.8	0.0	0.3
26	F	Paper	25.8	349.3	7.4	2.2	0.1	4.6
28	CA	Tinplate	–	–	–	3.4	2.6	77.4
29	CO	Plastic	0.8	8.8	8.6	11.1	0.5	4.9
30	F	Plastic	81,400.0	3,959,400.0	2.1	7275.0	19.5	0.3
31.1	F	Paper	–	–	–	37.0	2.8	7.5
31.2	F	Paper	–	–	–	8.0	2.8	35.0
32	CO	Plastic	80.2	2000.0	4.0	–	–	–

*Type of post-harvest processing: CA, canning; F, freezing; CH, chilling; CO, cooking.

(Williams et al., 2012). Also, if packaging has inappropriate opening devices it can cause food spill (Duizer et al., 2009). Although some LCA studies on seafood products evaluated FLW (Vázquez-Rowe et al., 2011, 2014), none of them assessed the influence of packaging on FLW. Due to high environmental impact from seafood production, there is a high potential of improvements by reducing FLW along the supply chain, especially at the household, where the climate impact associated with the wasted food part (meat, fish, and egg together) can contribute more than packaging materials, 18% against 2%, respectively (Verghese et al., 2014). This is a major point for canning products, since their packaging enables a longer shelf life, storage with no refrigeration and also slower transportation, and considerably less losses, than those of fresh/chilled products (Almeida et al., 2015; Winther et al., 2020). Thus, further LCA studies are needed to estimate to which extent the type of packaging can affect seafood waste and how improvements in materials or product forms might reduce its associated impacts.

Alternatives to plastic-based packaging are one of the challenges of the seafood industry. For instance, polystyrene, a single-polymer foam globally used both for packaging and insulation purposes, is widely used to transport fish. It has environmental costs throughout its production, use and disposal, and is a major component of terrestrial and marine litter (FIDRA, 2020). In fact, impacts related to plastic leakage and subsequent fate of polymers and/or their products once these have been released to the marine environment are not considered in LCA and can result in underestimated impacts associated to plastic-based packaging. More knowledge is needed on the characteristics of macroplastics (e.g., type of plastic, shape, colors most likely to lead to cases of entanglement, and ingestion) and on the hazardousness of substances found in the microplastics (e.g., additive content) (Ryberg et al., 2018). Packaging fate plays a key role in the environmental burden of packaging and progresses to include plastic leakage both at the inventory and impact assessment steps of LCA will enable a fair comparison between plastic and its substitutes (Woods et al., 2021).

Recycling is a common end-of-life route considered in LCA studies and for some materials (e.g., aluminum, glass, paper, plastics) it provides more environmental benefits than other waste-management options (Michaud et al., 2011). Avoided GHG emissions from the recovery of materials is highest for aluminum cans, with −8143 kg CO_2e per tonne of material collected for recycling, and large for mixed plastics and mixed glasses, with emission factors of −1024 and −314 kg CO_2e per tonne, respectively (Turner et al., 2015). However, benefits from recycling are mainly achieved by avoiding production of virgin materials, which is not the case so far since packaging materials entering to recycling, for example, in Europe, represent between 57% for paper and 19% for plastic (Tallentire & Steubing, 2020). Due to the low capacity of recycled materials treatment, large quantities of plastics are exported to other countries, and transportation or less efficient treatments of wasted material may lead to higher GHGs emissions elsewhere (Frei & Vazquez-Brust, 2020; Spierling et al., 2020; Wojnowska-Baryła et al., 2020). Also, to maintain the effectiveness of mechanical or chemical recycling of plastic, bio-based materials need to be separated, and composted with biowaste, another option for recycling (Wojnowska-Baryła et al., 2020). Due to these limitations of current waste-management systems, whilst recycling is an important part of the circular economy, extending the lifetime or phasing out products is also essential (Tallentire & Steubing, 2020). Therefore, apart from recycling, other end-of-life forms as reuse, energy recovery (e.g., for types of plastic that cannot be recycled) or disposal (e.g., landfill, anaerobic digestion compost) should be assessed (Spierling et al., 2020).

Waste streams from the seafood sector can also be part of the transition from a linear to a circular economy (Ruiz-Salmón et al., 2020). Bio-based materials such as gelatin from fish trimmings, chitosan from crustacean, and mollusk shells are viable candidates for displacement of conventional fossil fuel derived materials (Barros et al., 2009; de la Caba et al., 2019). Chitosan films and chitosan-based nanocomposites have been presented as an alternative for plastic in seafood packaging (de la Caba et al., 2019; Kakaei & Shahbazi, 2016; Qiu et al., 2014). Chitosan is biodegradable, provides antimicrobial activity, and offers film-forming properties that extend shelf life and prevent spoilage (Alves et al., 2018). Due to its relevance, studies on chitosan's environmental cost and market accessibility would be important to promote its development and foster the transition to a circular economy. As valorization of wastes become more common, it is important that seafood derived feedstocks do not repeat errors of other bio-based materials. Spierling et al. (2020) highlight the lack of diversity in bio-based materials and end-of-life options considered. Methodological gaps in biomaterials assessment need to be addressed primarily in composting or landfilling, where bio-plastics can have higher GHGs emissions than fossil fuel derived ones (de la Caba et al., 2019; Ingrao et al., 2015). Due to trade-offs related to other impact categories apart from climate change, such as ecotoxicity and eutrophication, LCA can help in identifying materials with the best overall environmental performance considering the complete life cycle of materials, from production to end-of-life options.

Another stream of research is on the reduction of packaging and extension of shelf life using skin packaging in combination with super chilling storage (Duran-Montgé et al., 2015). Innovative techniques such as intelligent packaging systems may also contribute to prolong shelf life, enabling effective cold chain management and food waste reduction (Janjarasskul & Suppakul, 2018; Tsironi & Taoukis, 2018). Packaging is among the opportunities to improve seafood industry and its potential for market and product sustainability can accelerate innovations.

4 | CONCLUSIONS AND RECOMMENDATIONS

Packaging is essential to guarantee food quality and minimize waste and other associated potential environmental impacts. However, unpackaged products can be less expensive and signal freshness or confidence in their origin. Optimizing all these (sometimes opposing) variables is challenging in food packaging. In the case of seafood, packaging has demonstrated to contribute to the total environmental impact along the whole supply chain independently of the species, aquaculture type, or fishing gear. Therefore, the sum of the potential environmental impacts of packaging production and further stages related to packaging (e.g., transport, storage, food preparation, food waste, reuse, or disposal) cannot be neglected.

Seafood LCAs focus mainly on the direct environmental impact coming from the packaging materials, to which some articles develop sensitivity analysis related to materials substitution. The most common recommendations to reduce this impact are either to reduce packaging volume or weight, or to substitute materials. Direct impacts related to packaging end-of-life have also been evaluated, and the most common recommendation is to increase recycling rate. However, recycling depends on many factors as the recyclability rate of materials and infrastructure or facilities capable of recycling these materials. Besides, independent of how much materials are recycled, if packaging production and its disposal do not decrease, part of the environmental burden will continue. For these reasons, accurate recovery rates, other packaging end-of-life forms such as reuse, and different disposal choices of packaging (e.g., anaerobic digestion compost) should also be considered.

Apart from the household preparation, other indirect environmental impacts derived from packaging related to transport, storage requirements, FLW avoidance, or the application of packaging innovations are often underconsidered, but could lead to a reduction of the overall environmental impact of seafood products. Avoidance of seafood waste throughout the supply chain is especially relevant due to the spoilage potential of seafood when compared to other foods. Therefore, future LCA studies should explore further the extent to which packaging can affect seafood waste and how packaging materials and design options can mitigate these impacts throughout the supply chain.

The nature of both the post-harvesting processing and the type of material has a great influence on the packaging contribution to the total environmental impact of the product. Packaging from canned products has a significant environmental contribution and the highest in comparison to other types of products. However, canned seafood may present other benefits like a longer shelf life and do not require energy for conservation. These aspects should be further investigated in a more holistic environmental assessment of seafood products. The packaging material production is more relevant to aluminum, tinplate, and glass than for plastic and paper. Therefore, it is essential to accurately include these materials and their associated operations in processing inventories (e.g., metal cans modeling). The mass ratio of the packaging is not very important with the exception of glass, but a reduction of packaging weight with respect to the food product would be an advantage.

Within the articles analyzed, it was noted that a limited number of LCA seafood studies include packaging and, in some cases, inventory data is not presented in detail, or contribution to the total impact assessment is unclear. Therefore, detailed information about packaging would be relevant to further understand whether differences between seafood LCA studies are related to impacts from assumptions on packaging materials or modeling choices for packaging processes. Overall, more LCA studies are needed to consistently map different seafood products, different packaging, and cover complete supply chains, as well as in the development of any novel packaging material or waste valorization strategies.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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