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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Life cycle assessment of importing canned tuna into Aruba through different supply chains, in varying can sizes and in oils, brine or tomato sauce

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Abstract

Purpose About 82% of the seafood consumed in Aruba is imported. Among canned fish products, tuna is consumed mostly. The purpose of this research was to compare the environmental impact of different types of canned tuna, and to identify environmental hotspots within the supply chains. Three comparisons were made: between three different supply chains (brands) of canned tuna, between six different accompanying liquids (oils, brine, and tomato sauce), and between small and large cans.

Methods Life cycle assessment (LCA) was used to calculate the environmental impact of "1 kg edible tuna at the distribution center in Aruba, including packaging," from the fishing stage until the distribution center in Aruba. An Agribalyse tuna model was selected as the basis of the models and was adjusted in SimaPro. Adjusted processes were tuna species consumption mix, electricity mix during canning, size of cans, packaging, sea, and truck transport, accompanying liquids, and storage. Added processes were transport in country of origin, and use of frozen loins (for one supply chain).

Results and discussion Generally speaking, the observed differences in environmental impact in the three different comparisons were quite small. After normalization, seven environmental impact indicators were selected as most relevant. Environmental hotspots were usually related to diesel combustion on the fishing vessel, or to steel production in the canning stage. Although packaging was modelled with attention to detail, and sea transport was modelled with attention to detail for the used vessels and vessel characteristics, these were not one of the environmental hotspots.

Conclusions and recommendations Although differences in environmental impact were quite small, most outstanding were that canned tuna that had the longest and partly frozen sea transport supply chain had the highest environmental impact. Preference should be given to local canning activities instead of shipping frozen tuna over long distances before canning. Furthermore, large cans always had a lower environmental impact compared to small cans. From a hospitality or consumer point of view, it can be recommended to select larger can sizes where practically possible. The choice of tuna canned in tomato sauce, oil, or brine would necessitate an analysis including the subsequent steps, for example, tuna canned in tomato sauce may be part of a meal as such, while tuna canned in brine may be prepared, after opening the can, with another warm or cold sauce, which would lead to additional separate impacts for these sauces.

Keywords Seafood · Aruba · Life cycle assessment (LCA) · Tuna · Supply chain

1 Introduction

Global seafood production is increasing year after year. Aquaculture production in particular is on the rise. Within the period 1990–2018, the global aquaculture production increased by 527% (FAO 2020a). The global seafood production is expected to continue to grow due to the increasing world population and increasing demand for animal protein especially in emerging countries where income is growing (Farmery et al. 2014; FAO 2020b). In wild-capture fisheries, the production and combustion of fossil fuel used on the vessels appear to be the main sources of greenhouse gases (GHGs) (Vázquez-Rowe et al.

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2012). Seventy-five to ninety-five percent of the total carbon footprint of wild-captured species can be traced back to the fishing stage with fuel use as main driver. The second most important driver of GHGs during the fishing stage is the use of refrigerants on the fishing boats (Ziegler et al. 2016). Capture fisheries also affect the stock size of target and non-target species, cause physical changes in the seabed, release chemicals and waste in the ocean, and cause eutrophication (Pelletier et al. 2007; Vázquez-Rowe et al. 2012; Farmery et al. 2014; O'Neill and Ivanović 2016).

One of the biggest gaps in seafood LCA is the gap in geographic coverage. As also highlighted in the research of Vázquez-Rowe et al. (2012) and by Prof. Peter Tyedmers during his invited lecture on seafood sustainability at LCA-Food 2022 (Lima, Perú), seafood LCAs are strongly biased towards industrialized countries. Moreover, the lack of transparency in seafood LCA literature results in a big data hurdle for those who want to perform a seafood LCA. Most of the authors do not reveal which life cycle inventory (LCI) data they used and which assumptions they made, making it difficult for others to further build on their findings. Also, the LCI databases which are available such as ecoinvent and Agri-footprint contain restricted data concerning seafood production (Bohnes and Laurent 2021). These challenges impede the widespread adoption of seafood LCA, making it difficult to assess the environmental impact of these products (Bohnes et al. 2019).

In Aruba, an island in the Dutch Caribbean situated north to Venezuela, the average seafood consumption per capita was 53 kg per year (in 2015–2017). In the same period, the global average seafood consumption per capita was 20 kg, showing that the seafood consumption in Aruba is high (National Marine Fisheries Service 2021). The Aruban seafood production, however, is rather low compared with the demand. Approximately 82% of the seafood consumed in Aruba is imported (own calculations based on Pauly et al. 2015; personal communication Central Bureau of Statistics (CBS) Aruba, dataset food imports 2019, September 9, 2020). Typical about Aruba's fish imports is that most registered fish imports are by sea (~94%) rather than by air (own calculations based on personal communication Central Bureau of Statistics (CBS) Aruba, dataset food imports 2019, September 9, 2020). Fish imported by sea arrives mostly frozen or in cans. Compared to other canned fish products, people spent most (69%) of their budget on canned tuna (Central Bureau of Statistics Aruba 2019).

In 2018, skipjack tuna (Katsuwonus pelamis) was the third most captured species worldwide following anchoveta and Alaska pollock (FAO 2020a). Sixty-four percent of the world's tuna products originate from the Pacific Ocean, and the dominant fishing technique is purse seining. Skipjack, albacore (*Thunnus alalunga*), and yellowfin (*Thunnus albacares*) tuna are mainly used for the canning industry, while bluefin (*Thunnus thynnus*) and bigeye tuna (*Thunnus obesus*) are the main species used for sashimi and sushi. The world's top exporter of canned and processed tuna is Thailand with Bangkok being the heart of the global tuna processing industry. The largest importers of processed and canned tuna are the USA and the European Union (FAO 2021).

The objective of this research is to assess the environmental impact and environmental hotspots of different brands and types of canned tuna imports into Aruba, with a focus on three comparisons. First, the environmental impact of three different brands of canned tuna, originating from Thailand or Peru. Second, the environmental impact of six different accompanying liquids, i.e., oils or sauces. Third, the environmental impact of a small (0.142 kg) and a large (1.88 kg) can size. The larger cans are sold in supermarkets but also used in the hospitality industry. To our knowledge, comparisons between the environmental impact of tuna can sizes and between different accompanying liquids have not been made before. Moreover, we will provide extensive details on our methods, such as the use of LCIs and databases.

2 Methods

The ISO 14040 and the ISO 14044 standards were used in this study (European Commission et al. 2010).

2.1 Data collection

First, we identified the target products, as described in Sect. 2.2. After describing the goals and scope in Sect. 2.3, we collected detailed data on the supply chains (see Sect. 2.4) of the different brands of canned tuna by interpreting information on the packaging, through various online sources, and by materials provided by stakeholders in Aruba.

2.2 Identification of target products

To make a realistic selection of the types of canned tuna sold in Aruba, seven differently sized supermarkets were visited in May 2021 and pictures were taken of the shelfs and individual products (Fig. 1). It was assumed that the number of facings represented the popularity of a specific type of canned tuna. The most abundant brands were Sa-Pac, Brunswick, Santa Rita, Chicken of the Sea, and Bumble Bee. Canned tuna brands with different supply chain characteristics were chosen to study in this paper. Santa Rita and Sa-Pac tuna were caught and canned in Peru and Thailand, respectively. Tuna from the three other brands was caught and pre-processed into frozen loins in Thailand and shipped to the cannery in the USA. As most information was available on the Chicken of the Sea supply chain, the brands Brunswick and Bumble Bee were not selected for this study. Most of the tuna sold in Aruba is canned in vegetable,

Fig. 1 Canned tuna products in a supermarket in Aruba. The upper picture shows Sa-Pac and Santa Rita canned tuna. The picture below shows Chicken of the Sea canned tuna

sunflower, or soybean oil. Other liquids such as brine, olive oil, and tomato sauce are sold as well in lower amounts.

2.3 Goal and scope definition

The goal of this study is to assess the environmental impact of canned tuna imported in Aruba, and to compare the environmental impact of different tuna supply chains, different accompanying liquids, and different can sizes. By performing an attributional LCA, environmental hotspots in the seafood supply chains could be identified.

The functional unit is 1 kg edible tuna at the distribution center in Aruba, including packaging. This study performs a cradle-to-gate LCA for in which the gate refers to the gate of the distribution center in Aruba. All transport steps between the different supply chain stages were considered, as well as the transport of the packaging material. Figure 2 shows the system boundaries as well as a representation of how the Agribalyse tuna process was adjusted in this study. The colored boxes and texts indicate which processes were adjusted (beige), except necessary scaling, or added (turquoise). Now, details of the supply chains and the depicted adjustments will be discussed.

2.4 Process description and Life Cycle Inventory

The Agribalyse tuna process was used as the basis for this research: "Tuna, flaked, in oil, canned, drained, processed in FR | Ambient (average) | Already packed—Aluminium | at distribution/FR." It was modified to the Aruban case study by adapting the geographical range, the packaging material, and the transport routes and modes. The background processes in Agribalyse® originate from the database ecoinvent. To adjust the tuna model, background processes of the databases ecoinvent and Agri-footprint were used. Seafood datasets from Agribalyse use the system model "Allocation, cut-off." The reason Agribalyse uses this system model as default for seafood datasets is a lack of data on the multifunctionality of seafood products (Asselin-Balençon et al. 2020). Therefore, this system model was also selected when datasets from the database ecoinvent were used.

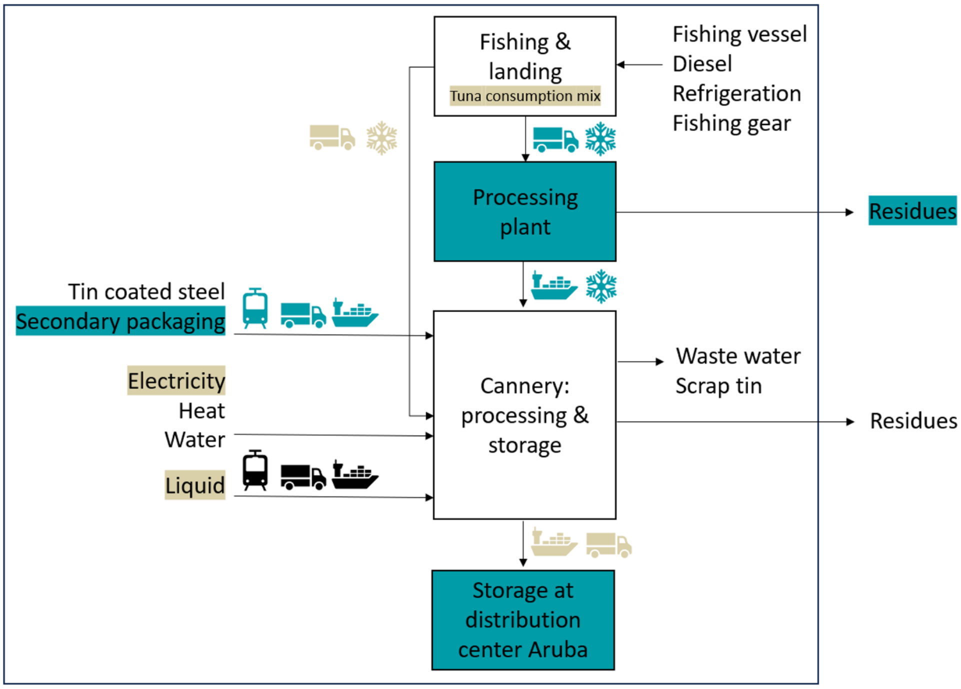

Fig. 2 System boundaries of canned tuna imports into Aruba, and graphical representation of the canned tuna models based on the Agribalyse process "Tuna, flaked in oil, canned, drained, processed in FR | Ambient (average) | Already packed Aluminium | at distribution/FR." The white boxes and texts indicate the processes were only changed by scaling to our processes. Some processes were adjusted by adding primary data and/or improving geographic representation (beige). Finally, some new life cycle stages were added (turquoise)

2.4.1 Fishing stage

The tuna system started with the fishing activity, related to fishing and fish on vessels. This included the construction, maintenance, and end-of-life treatment of the vessels and the fishing gear. The Agribalyse model on the fishing stage was adjusted by altering the caught species. Chicken of the Sea tuna includes the species skipjack, yellowfin, and albacore tuna (Chicken of the Sea 2020). Sa-Pac and Santa Rita did not disclose information on the tuna species in their products. As not sufficient information was available for all brands, we assumed a similar tuna mix of 90% skipjack tuna and 10% yellowfin tuna.

LCIs of wild capture and aquaculture in the context of the Sustainable Recycling Industry program where the ecoinvent association is in charge of developing national LCA data in several regions and countries are available in the report of Avadí et al. (2019). Herein, a fuel use efficiency (FUE, i.e., the volume of diesel that is needed to capture and land 1 ton of fish) of 831.6 L/t in Ecuador is indicated as being similar to FUE values reported for other purse seining tuna fisheries reported in Parker and Tyedmers (2014). Hence, the fishing stage Agribalyse model was not adapted to the specific fishing areas in this study. Instead, the LCI was based on a float of four worldwide average fishing vessels for tuna using purse seine fishing.

2.4.2 Truck transport

For all products, truck transport occurred between the fishing port and the processing facility, between the processing facility and the export port, and from the port of Barcadera in Aruba to the distribution center in Aruba. For Chicken of the Sea, truck transport also occurred between the port and the cannery in the USA. The transport between the fishing harbor and the processing facility occurred without packaging in a refrigerated truck (Noal Farm 2018). This was modelled with the ecoinvent process "Transport, freight, lorry with reefer, freezing {GLO}| market for | Cut-off, S." The transport step from the cannery to the export port was modelled with the ecoinvent process "Transport, freight, lorry 16–32 metric ton, EURO*X* {GLO}| market for | Cut-off, S." EURO norms used for modelling truck transport are depicted in Table 1.

Chicken of the Sea canned tuna was caught in the FAO Area 71 in the Western Central Pacific Ocean. The caught tuna was processed into frozen loins in Thailand in a Thai Union facility, this was assumed to be the Thai Union Manufacturing Plant 2, which was located 10 km from the fishing port and 45 km from the Port of Bangkok. After pre-processing, the frozen loins were shipped in a reefer (i.e., a refrigerated container) to the cannery in Lyons in the USA to be further processed into

Table 1 EURO norms in countries where truck transport was modelled

Country	EURO norm	Source
Vietnam	EURO4	(EMLEG, 2018)
Thailand	EURO3	(TransportPolicy.net, 2018a)
Peru	EURO4	(TransportPolicy.net, 2018b)
Europe	EURO6	(Velders et al., 2013)
USA	EURO6	(TransportPolicy.net, 2018c)

canned tuna. This port was chosen as it was located closest to the Port of Savannah (Chicken of the Sea 2020). The distance from the port of Savannah to the cannery was 135 km.

Santa Rita canned tuna was caught in Peru and canned in the canning factory "Inversiones y Comercio Internacional SRL" in Lima. The port of Callao was assumed to be both the fishing and export port; this port was located 20 km from the canning factory. The transport to the cannery was frozen transport, while the transport away from the cannery was ambient. The canned tuna was exported by ship via Cartagena in Colombia.

Sa-Pac canned tuna was caught and canned in Thailand. The canning and processing facility was Unicord Public Company Limited. A fishing port along the Tha Chin River located 10 km from the processing facility was chosen as representative fishing port. The processing facility was located 45 km from the Port of Bangkok. From there, the tuna was shipped directly from Thailand to Aruba, without passing by any distribution center.

2.4.3 Packaging

The primary packaging was adjusted by using the weights of small tuna cans collected in Aruba, and the weight of a large tuna can from a restaurant in Aruba. The amount of oil and tinplate used in this process was adapted to the amount of oil and tinplate used in the tuna cans that are most commonly sold in supermarkets or used by restaurants in Aruba, i.e., tuna cans with a net weight of 142 and 1880 g, for small and large cans respectively. Their drained weights were 113 and 1498 g, respectively. For small and large cans, 0.022 and 0.01 m^2 of tin-plated steel were used per kilogram drained tuna, respectively.

Agribalyse used the conversion ratio 1 kg drained tuna/1.33 kg canned tuna. This conversion ratio, however, was adapted to the conversion ratio of canned tuna products in this study, 1 kg drained tuna/1.61 kg canned tuna. The conversion ratios used for modelling are depicted in Table 2.

Secondary packaging was included by adding cardboard boxes, EUR-pallets, and the plastic around the boxes on the pallets. The weight and amount of cardboard boxes and pallets used were determined by interpolation of the data from the study of Hospido et al. (2006) (Table 3). In this study, the secondary packaging material is described for 660 kg drained tuna canned in small cans with an individual drained weight of 62 g. Although the can size this research focuses on is larger, the assumption was made that the weight of the secondary packaging material was similar to the cans with a drained weight of 62 g. EUR-pallets weighed 25 kg and are not re-used in Aruba but collected to use for other purposes (personal communication wholesaler Aruba, Feb 20, 2022). The plastic wrap weighed 0.64 kg and was obtained from an importer in Aruba.

Table 2 Drained tuna weight and packaging weight of a tuna can with 113 g drained tuna and the packaging weight of 1 kg drained tuna canned in cans with a net weight of 113 g

	Tuna can with 113 g drained tuna	1 kg drained tuna canned in cans with a net weight of 113 g
Drained weight (kg)	0.113	1
Can weight (kg)	0.040	0.354
Oil weight (kg)	0.029	0.257
Bruto weight (kg)	0.182	1.611

Table 3 Weight of secondary packaging material for 660 kg drained tuna and 1 kg drained tuna based on Hospido et al. (2006)

Packaging material	660 kg drained tuna	1 kg drained tuna
Cardboard box (kg)	92.01	0.14
Plastic film (kg)	5.42	0.01
Pallet (unit)	2.08	0.003

Transport of the packaging materials was modelled using default distances specified by the Product Environmental Footprint Category Rules Guidance (PEFCR) of the European Commissions (European Commission 2017). It was assumed that the EURO norm of vehicles in each country complied with the obligated Euro norm for that country (see Table 1). Although none of the focus species is packed in Europe, the PEFCR values were used since no such detailed default transport distances are available for other regions of the world. To model the transport distances, the PEFCR differentiates two transport scenarios: the packaging supplier of the European packaging facility is located outside Europe or within Europe. It was assumed that the factory of the packaging material was not located on a different continent than the packaging facility. Therefore, the distances of the scenario of a packaging supplier within Europe were assumed. Distances and LCIs used, as specified by the PEFCR document, are depicted in Table 4.

The PEFCR document also specifies which ecoinvent transport processes should be used. The European geographic range {RER} was substituted for the correct geographic range of the lorry, train, and ship transport. Additionally, the Euro norm of the lorry transport specified by the PEFCR (EURO6) was substituted for the obligated Euro norm in the country/geographic range of the packaging facility (Table 1).

2.4.4 Accompanying liquids

The Agribalyse model assumed canning in vegetable oil, which was a mixture of 6.62% cottonseed oil, 47.05% palm oil, and 46.33% soybean oil. To model the different accompanying liquids, the LCIs depicted in Table 5 were selected. For small and large cans, 257 g and 382 g of accompanying liquid were used per kilogram drained tuna, respectively.

Table 4 Default transport distances and ecoinvent processes for packaging material from a supplier within Europe to a European packaging facility based on the PEFCR

Transport mode	Transport distance (km)	Ecoinvent process
Lorry	230	Transport, freight, lorry 16–32 metric ton, euro6 {RER}| market for transport, freight, lorry 16–32 metric ton, EURO6	Cut-off, S
Freight train	280	Transport, freight train {RER}| market group for transport, freight train	Cut-off, S
Barge ship	360	Transport, freight, inland waterways, barge {RER}| processing	Cut-off, S

Table 5 SimaPro processes that substitute for the ecoinvent process "Vegetable oil, refined {GLO}| market for | Cut-off, U" for the different accompanying liquids

Canning style	*SimaPro process*	*Database*
Tuna canned in brine	Tap water {GLO}| market group for	Cut-off, U	ecoinvent
Tuna canned in soybean oil	Soybean oil, at plant/FR U	Agribalyse
Tuna canned in sunflower oil	Sunflower oil, at plant/FR U	Agribalyse
Tuna canned in olive oil	Olive oil, at plant/FR U	Agribalyse
Tuna canned in tomato sauce	Basque-style sauce or tomato sauce with sweet peppers, prepacked, at plant/FR U	Agribalyse

2.4.5 Overseas transport

To model the shipping routes, durations, and distances, we used the schedule on cma-cgm.com, which is one of the largest shipping companies (AXSMarine 2022). The possible routes were the same for Chicken of the Sea and Santa Rita canned tuna, and two different routes were possible for Sa-Pac canned tuna. For Sa-Pac tuna, an average route was based on two possible routes. Details on transshipments, ports, ship size, sailing distances, and transit days are provided in Table 6. Ship size was determined via marinetraffic.com, expressed as deadweight tonnage (DWT).

The DWT of a ship indicates the load capacity. It is the total weight of cargo, fresh water, ballast water, fuel, passengers, provisions, and crew. The summer DWT differs from the winter DWT since the density of water declines in summer due to thermal expansion. Consequently, a sea ship floats deeper in the water during summer and can carry less cargo (Maritime Impact 2020).

LCIs from Agri-footprint were used as these allowed to select different characteristics, such as DWT, load factor (LF), distance (short, middle, long), "default," or "empty return." It was assumed that all ships had an LF of 100%, except for the ship with the last transshipment to Aruba,

Table 6 Container ships used for the average route of the different tuna brands to Aruba

Route	Trips between ports	Summer DWT	Distance (km)	Total distance (km)	Average total distance (km)	Average total transit days
Sa-Pac tuna						
1. Thailand–South Korea–Jamaica–Aruba	Bangkok → Busan	15,000	5600	23,065	26,024	43.1
	Busan → Kingston	120,000	16,525			
	Kingston → Barcadera	10,000	940			
2. Thailand–Hong Kong–Panama–Aruba	Bangkok → Hong Kong	15,000	2708	28,982		
	Hong Kong → Colón	120,000	24,630			
	Colón → Barcadera	10,000	1644			
Santa-Rita tuna						
Peru–Colombia–Aruba	Callao → Cartagena	120,000	3140	4932	4932	13.1
	Cartagena → Barcadera	15,000	1792			
Chicken of the Sea tuna						
Thailand –Singapore–USA–Jamaica–Aruba	Frozen: Bangkok → Singapore	15,000	1526	29,858	29,858	Frozen: 43.5 Ambient: 12.2
	Frozen: Singapore → Savannah	120,000	24,764			
	Ambient: Savannah → Kingston	10,000	2383			
	Ambient: Kingston → Barcadera	15,000	1185			

which was assumed to have a LF of 80%, since Aruba is not situated at a main maritime transport route. All ships arriving in transhipment ports were assumed "default." The ships of the last transshipment were assumed to have an "empty return," due to Aruba's limited exports. This is modelled as the return trip of the same distance with a 0% LF. "Default" considers that sea ships may travel to a next port to pick up new load instead of returning to the original port of loading. To account for the refrigeration during transport, the LCI "Operation, reefer, freezing {GLO}| market for | Cut-off, S", expressed in kg*day, was selected.

2.4.6 Storage

Ambient storage was modelled according to the PEF guidance document (Asselin-Balençon et al. 2020), similar to Agribalyse's methodology. For Chicken of the Sea canned tuna, it was assumed that no frozen storage occurred at the pre-processing plant in Thailand. It was assumed that products remained stored for 1 year.

2.5 Life cycle impact assessment (LCIA)

The three mandatory steps of an LCIA — selection, classification, and characterization — were performed by the LCIA method ILCD 2011 Midpoint + in SimaPro. Table 7 depicts an overview of all impact categories, their abbreviations, and unit.

External normalization of the environmental impacts was performed to interpret the results better. This optional step in LCIA compares the calculated impact scores to the scores of a reference system, identifying the relative significance of a certain impact score (Laurent and Hauschild 2015). ILCD uses the normalization factors recommended by the Joint Research Centre which reflect the total impact of an average European person for the different impact categories for the reference year 2010 (Benini et al. 2014; Rosenbaum et al. 2018). Although the lifestyle of Europeans is different from the lifestyle of Arubans, the adoption of the average European impacts is justified by the fact that these impacts are the most up-to-date and reliable impacts.

The impact categories that were identified as relevant contribute together to more than 80% of the total normalized impact of one scenario. This threshold was based on the PEFCR guidance document (European Commission 2017). Following the PEFCR guidance document, the three toxicity-related impact categories — HTCE, HTNCE, and FRTOX — were excluded from the normalization step (European Commission 2017). This is because the normalization factors in the model behind these impact categories (USEtox model) are not sufficiently robust (Fazio et al. 2018a, b). The impact category IRE was excluded as well since this impact category is not yet fully developed.

A contribution analysis was performed for the impact categories that were identified as most contributing to the total normalized impact. An additional weighting step was not

Table 7 ILCD 2011 Midpoint + impact categories

Impact category	Abbreviation	Unit
Climate change	CC	kg CO_2 eq
Ozone depletion	ODP	kg CFC-11 eq
Human toxicity, cancer effects	HTCE	CTUh (comparative toxic unit for humans)
Human toxicity, non-cancer effects	HTNCE	CTUh (comparative toxic unit for humans)
Particulate matter	PM	kg PM2.5 eq
Ionizing radiation HH (human health)	IRHH	kBq U^{235} eq (to air)
Ionizing radiation E (ecosystem)	IRE	CTUe (comparative toxic unit for ecosystems)
Photochemical ozone formation	POF	kg NMVOC eq
Acidification	AC	molc H + eq
Terrestrial eutrophication	EUTT	molc N eq
Freshwater eutrophication	EUTF	kg P eq
Marine eutrophication	EUTM	kg N eq
Freshwater ecotoxicity	FRTOX	CTUe
Land use	LU	kg C deficit
Water resource depletion	WD	m^3 water use related to local scarcity of water
Mineral, fossil, and renewable resource depletion	MFRRD	kg Sb (antimony) eq

performed since the ILCD method assigns equal weights to all impact categories (European Commission 2016).

3 Results and discussion

The objective of this research was to assess the environmental impact and environmental hotspots of different brands and types of canned tuna imports into Aruba, with a focus on three comparisons. First, the environmental impact of three different brands of canned tuna (Sect. 3.2), originating from Thailand or Peru. Second, the environmental impact of six different accompanying liquids, i.e., oils or sauces (Sect. 3.3). Third, the environmental impact of a small (0.142 kg) and a large (1.88 kg) can size (Sect. 3.4). A normalization step was carried out first to identify the most relevant impact categories (Sect. 3.1).

3.1 Normalization and identification relevant impact categories

By performing an external normalization step (Table 8), the most relevant impact categories could be identified.

Similar values were found for the different comparisons. The environmental impact indicators considered in this study are climate change (CC), particulate matter (PM), ionizing radiation human health (IRHH), photochemical ozone formation (POF), acidification (AC), terrestrial eutrophication (EUTT), and mineral, fossil, and renewable resource depletion (MFRRD). Although climate change was not one of the most contributing impact categories, it was included in this analysis because of its relevance in today's world.

3.2 Environmental impact of different supply chains

The environmental impact of the three different supply chains, based on tuna in vegetable oil in small cans, is depicted in Fig. 3. The three models show similar results. Being based on the same background data, the differences are resulting from the adaptations in the following life cycle stages: processing, truck transport, and sea transport. The highest environmental impact in all categories was found for Chicken of the Sea canned tuna from Thailand. Similar, and slightly lower results were found for Sa-Pac canned tuna from Thailand and Santa Rita canned tuna from Peru.

It stands out that the diesel combustion on the fishing vessel has the same environmental impact for supply chains from Peru and from Thailand: as indicated above, it is part of the background processes that were not adapted (see also Fig. 2), yet we made the choice to keep it visible in the results so that the processes that were adapted (Processing, Truck transport, and Sea transport) can be appreciated within the larger perspective.

For most impact categories, diesel combustion on the fishing vessel is the most contributing life cycle stage. The contribution of diesel combustion is particularly high for AC, EUTT, and POF, compared to other life cycle stages. AC by diesel combustion is caused by the release into the air of acidifying compounds, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3) (EEA 2020). These acidifying compounds cause EUTT after atmospheric deposition (Rosenbaum et al. 2018). POF by diesel combustion is caused by the emission of non-methane volatile organic compounds (NMVOCs) (Sun et al. 2018). Although NMVOCs are also emitted during metal production and combustion of fuels during sea freight (Siddiqui and Dincer 2021), these life cycle stages contribute less to the overall particulate ozone formation.

For some impact categories, the contribution of the tin-coated steel contributed more than in other impact categories, namely, for CC, IRHH, PM, and MFRRD. This was mainly due to steel production and not due to the tin. For CC, this was due to the electricity consumption and heat in the production process of steel, because of coal combustion. For IRHH, this was mostly due to electricity consumption, and for PM this was mostly due to the production of heat. IRHH was caused by the production of radionuclides, which have an ionizing potential, during electricity consumption (Frischknecht et al. 2000). To MFRRD, steel consumption contributed for about two-thirds, and tin consumption for about one-third. This indicates that tin is scarcer than steel, as a tin can mainly consist of steel. Another contributing life cycle stage to MFRRD was the fishing gear, due to the consumption of minerals including lead.

Figure 3 further indicates that generally the differences in environmental impact were mainly related to the sea transport and processing, including the tin for the cans. Chicken of the Sea canned tuna consistently had a higher environmental impact due to a longer overseas transport and, even more important, due to the frozen transport step of frozen loins from Thailand to the American cannery (corresponding to 80% of the total overseas transport time). The fact that the transport mode (refrigerated or frozen) matters more is visible when comparing the transport distances between Chicken of the Sea and Santa Rita, with the latter being only less than 4000 km shorter yet the bright blue being much less visible in Fig. 3. For Chicken of the Sea, the freezing contributed for 38–50% to the environmental impact of sea transport, for most impact categories. For MFRRD and IRHH, freezing contributed even for 75% and 74% to the environmental impact of sea transport, respectively.

As mentioned above, minor differences in the environmental impact of sea transport were observed due to differences in distance sailed. In addition, although different ship sizes were used between transshipments, this did not cause large differences in the environmental impact of sea transport for different supply chains. For all supply chains, most of the sea transport was by

Table 8 The contribution of each impact category to the total normalized impact of one scenario. The robustness level describes the reliability of the normalization factor of each impact category (Benini et al. 2014). The percentages in bold for one scenario contribute together to more than 80% of the total normalized impact of that scenario. Total normalized impacts may not add up to 100% due to rounding off the values

	Robustness level	Chicken of the Sea*	Sa-Pac*	Santa-Rita*	Small can, sunflower oil	Small can, soybean oil	Small can, olive oil	Small can, tomato sauce	Small can, brine	Small can, vegetable oil	Large can
Climate change	Very high	6%	6%	6%	5%	6%	5%	6%	6%	6%	5%
Ozone depletion	Medium	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Particulate matter	Very high	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**9%**
Ionizing radiation HH	Medium	**10%**	**10%**	**11%**	**12%**	**11%**	**11%**	**14%**	**12%**	**11%**	**11%**
Photochemical ozone formation	Medium	**13%**	**13%**	**13%**	**13%**	**12%**	**13%**	**13%**	**13%**	**13%**	**14%**
Acidification	High	**13%**	**13%**	**13%**	**13%**	**13%**	**13%**	**13%**	**14%**	**13%**	**14%**
Terrestrial eutrophication	Medium	**14%**	**14%**	**14%**	**14%**	**13%**	**14%**	**14%**	**14%**	**14%**	**15%**
Freshwater eutrophication	Medium to low	2%	2%	2%	2%	2%	2%	2%	2%	2%	1%
Marine eutrophication	Medium to low	9%	7%	7%	9%	7%	7%	7%	7%	7%	8%
Land use	Medium	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Water resource depletion	Medium to low	−1%	−1%	4%	−1%	−1%	4%	0%	−1%	1%	2%
Mineral, fossil and ren. resource depletion	Medium	**24%**	**23%**	**24%**	**24%**	**27%**	**21%**	**22%**	**22%**	**23%**	**21%**
Total normalized impact:		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Total contribution of most relevant impact categories:		85%	84%	84%	86%	86%	82%	86%	86%	84%	83%

*The normalization values of the three different supply chains were calculated based on small cans in vegetable oil

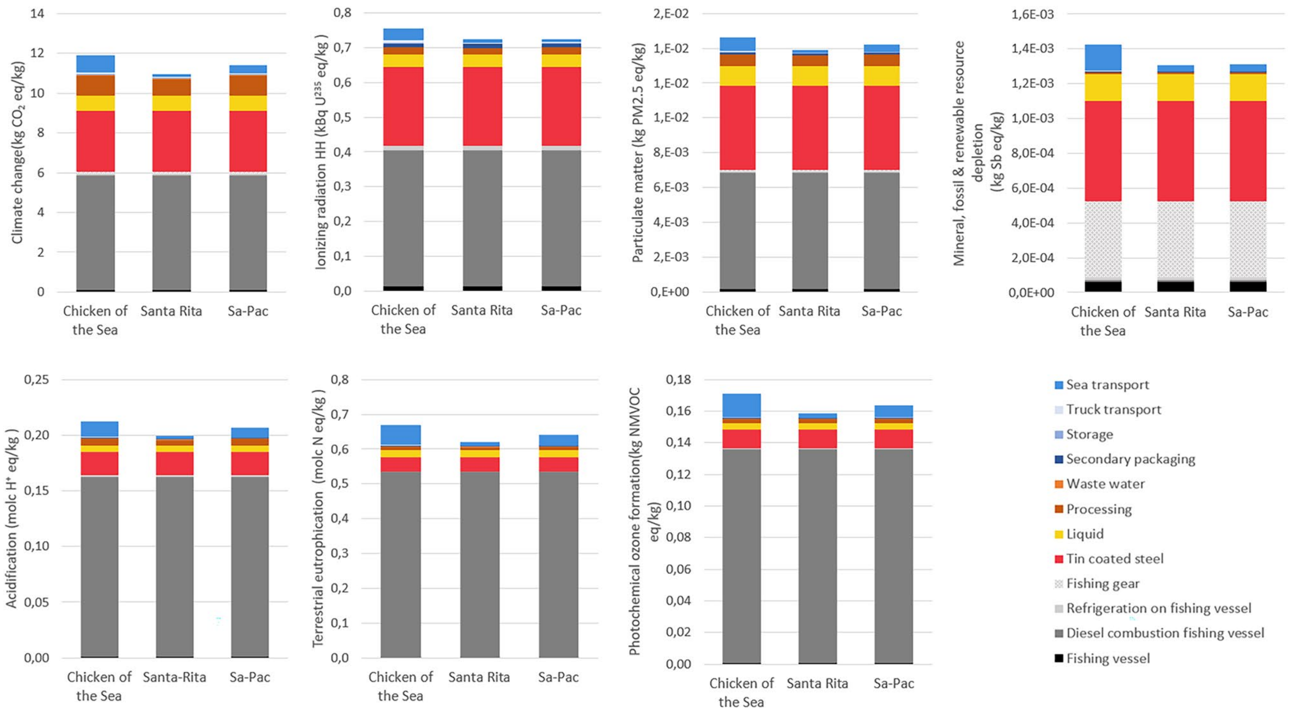

Fig. 3 Contribution analysis of three different canned tuna supply chains, for canned tuna in vegetable oil in small cans. The black and gray life cycle stages are related to fishing. The red and yellow life cycle stages are related to processing. The blue life cycle stages are related to distribution

relatively large ships. The ship size is measured by its DWT, and mostly a ship with a different size was used between transshipments. For all supply chains, the largest part of the overseas transport (72–85%) was by a relatively large container ship, of 120,000 DWT. While for the other transshipments a relatively small ship was used, of 10,000 or 15,000 DWT.

Some adjustments to the original Agribalyse process did not result in major differences between the supply chains. First, secondary packaging was modelled in detail by adding cardboard boxes, pallets, the plastic film around the boxes on the pallet, and transport of the packaging, and these did not contribute much to any of the environmental impacts. Second, there was no difference in the contribution of truck transport because the distance covered was similar for the different supply chains. Third, although the electricity during processing was adjusted, there was no difference in the environmental impact of processing between canned tuna from Peru or Thailand. The use of heat during processing often contributed more to the environmental impact of this life cycle stage than electricity, and this was not adjusted.

3.3 Environmental impact of different accompanying liquids

Due to the small differences in environmental impact between the different supply chains, as described above, an average supply chain was constructed to compare canned tuna with different accompanying liquids and in different can sizes. For both scenarios, one-third was assumed to be Chicken of the Sea, one-third Sa-Pac, and one-third Santa Rita canned tuna. For the small cans, the following six accompanying liquids were modelled: sunflower oil, soybean oil, olive oil, tomato sauce, vegetable oil, and brine. Results are shown in Fig. 4.

For most accompanying liquids, there was only a small difference in environmental impact, as the life cycle stages that contributed most had an identical value: diesel combustion during fishing, and the tin can. However, in some impact categories, there were larger differences. First, tuna canned in soybean oil had the highest impact for CC, due to land use change in soybean cultivation. The soybean oil process which was used, “Soybean oil, at plant/FR U,” was a mix of 60.3% Argentina, 20.4% USA, and 19.2% Brazil. Land use change took place in Argentina and Brazil due to the transformation of primary forest into arable land (Nemecek et al. 2016). Second, tuna canned in tomato sauce had the highest impact in the category IRHH. This was due to electricity consumption for cooking of the tomatoes, produced by nuclear power plants in France. Canned tuna in tomato sauce imported into Aruba may have a lower IRHH impact because Peru and Thailand do not rely on energy from nuclear power plants, but mainly on oil and gas; Peru’s energy is also for a large part produced by hydropower (bp 2022). Yet, there is no information on where the tomato sauce was produced and hence the original process remained unchanged. Third, tuna

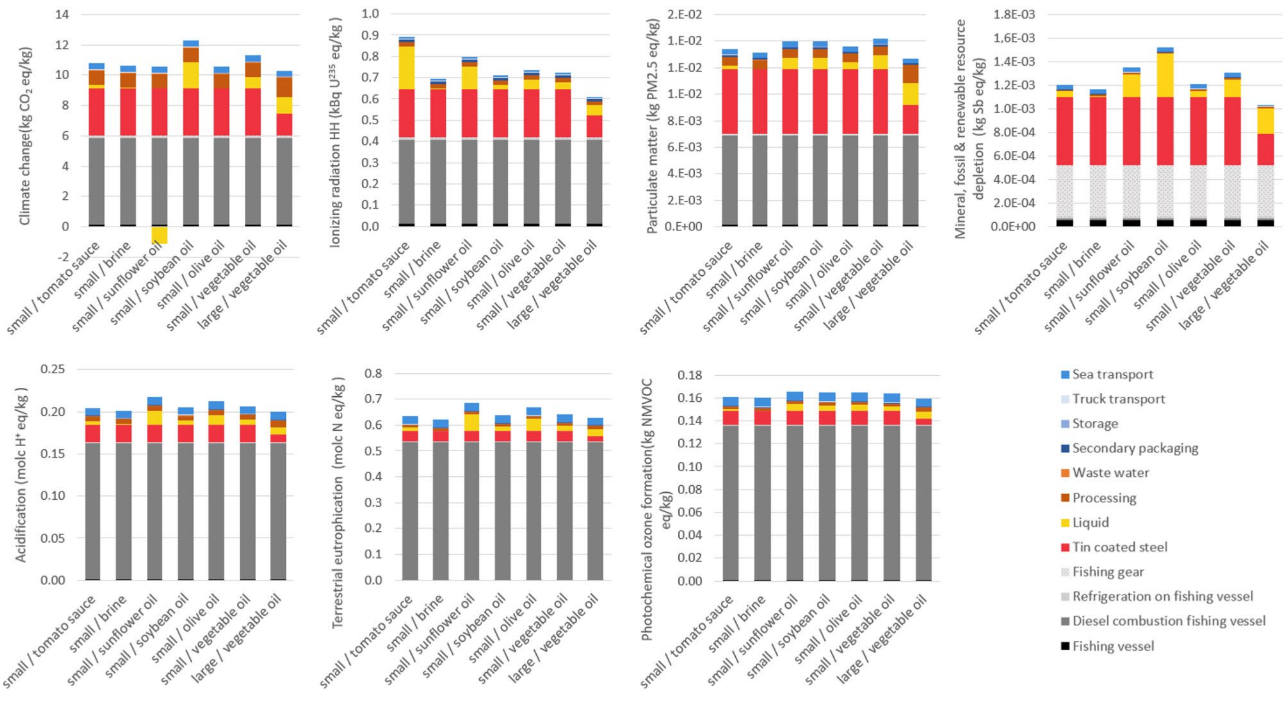

Fig. 4 Environmental impact of tuna canned in small cans in tomato sauce, in different oils, and in brine. Environmental impact of tuna canned in large cans in vegetable oil. The black and gray life cycle stages are related to fishing. The red and yellow life cycle stages are related to processing. The blue life cycle stages are related to distribution

canned in sunflower oil and olive oil had the highest impact for AC and EUTT, due to the farming process and not due to pressing of the sunflowers and olives.

3.4 Environmental impact of different can sizes

A comparison was made between small (142 g) and large (1.88 kg) canned tuna in vegetable oil (see Fig. 4). Large cans always have a lower environmental impact than small cans. This difference between small and large cans is larger in impact categories where the impact from "diesel combustion" is overall less dominating, namely CC, IRHH, PM, and MFRRD. For large cans, more vegetable oil and less tin are required, per kilogram edible tuna, resulting in an overall lower environmental impact. Avadí et al. (2014) also found that an increase in the amount of edible product per amount of packaging reduces the impact of canned products, per kilogram product. One of their results showed that the ReCiPe single score of canned anchoveta was 12% lower for a two times larger can size.

Avadí et al. (2015) performed an LCA on three different processed tuna products from Ecuador. The products that were assessed were canned tuna, pouched tuna, and vacuum-bagged tuna loins. The latter is a semi-finished product which is exported to canneries abroad. Overall, the main contributors to the products' environmental impact were the fuel use on the fishing vessels and the consumption of packaging material (tin cans in particular). Compared to the other two processed products, the canned tuna product showed the highest impact for all the impact categories assessed in this research (climate change, marine eutrophication, particulate matter formation, metal depletion, cumulative energy demand, marine ecotoxicity, and photochemical oxidant formation).

4 Conclusions

The objective of this research was to assess and compare the environmental impact and environmental hotspots of different types of canned tuna imported into Aruba. Moreover, the goal was to provide extensive details on the used methods.

Although the observed differences in environmental impact were quite small for most environmental impact indicators, some trends were observed. First, canned tuna from the Chicken of the Sea supply chain always had the highest environmental impact especially due to a long and for a large part frozen sea transport from Thailand to the USA. Preference should be given to local canning activities, close to the landing port. Second, for most accompanying liquids, there was only a small difference in environmental impact, as the life cycle stages that contributed most had an identical value: diesel combustion during fishing, and the tin can. Whether it is better to choose for brine in comparison with other accompanying liquids would necessitate an analysis including the subsequent steps, for example, tuna canned in tomato sauce may be part of a meal as such, while tuna canned in brine may be prepared, after opening the can, with another warm or cold sauce, which would lead to additional separate impacts for these sauces. Third, tuna canned in larger cans always had a lower environmental impact compared to tuna canned in smaller cans.

Although the 16 ILCD impact categories were included in this LCA, certain fishery-specific biologic impacts were not assessed since this was outside the scope of this study. These impacts include for example the potential decrease in stock sizes of target and non-target species and the impact of discharged fishing gear on sea life.

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Declarations

Conflict of interest The authors declare no conflict of interests.

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