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Exploring the environmental impacts of plastic packaging: A comprehensive life cycle analysis for seafood distribution crates

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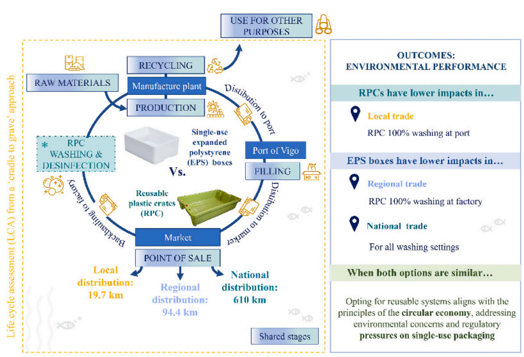
HIGHLIGHTS

- Packaging comparison: RPCs vs. EPS boxes in seafood distribution impact.
- Transportation key: Weight and distance crucial for environmental impacts.
- Future focus: Optimize packaging shelf life, enhance reuse cycles, and develop effective collection/washing.

GRAPHICAL ABSTRACT



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ABSTRACT

Annually, 8.3 million tonnes of mismanaged plastic waste enter oceans, prompting the food packaging industry, a major contributor, to minimize its environmental footprint. Within the seafood sector, a nascent number of studies are exploring the impacts of various packaging solutions for distribution, yet clear insights remain elusive. This study tries to fill the gap by comparing the impacts of two seafood packaging options: disposable expandable polystyrene (EPS) boxes and, for the first time, reusable plastic crates (RPC) crafted from high-density polyethylene. Using the life cycle assessment methodology with a 'cradle to grave' approach, the research evaluates the distribution of 1260,000 t of fish from port of Vigo (Spain) to various markets. Similar climate change values emerge in local ($5.00 \cdot 10^7$ kg CO_2 eq.) and regional trade ($1.20 \cdot 10^8$ kg CO_2 eq.) for both options, but RPCs exhibit around a 12 % increase ($6.15 \cdot 10^8$ kg CO_2 eq.) during national distribution, emphasizing package weight and load significance. The findings across all impact categories exhibited general consistent trends. The sensitivity analysis suggests relocating washing facilities to port could enhance RPCs' environmental benefits for transport within a 160 km range. These findings underscore reusable packaging's potential as an eco-

Acronyms: AC, Acidification; CC, Climate Change; EoL, End-of-Life; EPE, Expanded Polyethylene; EPS, Expandable Polystyrene; EU, European Union; EUF, Eutrophication—Freshwater; EUM, Eutrophication—Marine; FLW, Food Loss and Waste; FU, Functional Unit; HDPE, High-Density Polyethylene; ISO, International Organization for Standardization; LCA, Life Cycle Assessment; LCIA, Life Cycle Impact Assessment; PE, Polyethylene; PS, Polystyrene; PUR, Polyurethane; RPC, Reusable Plastic Crates; RUF, Resource Use—Fossils; UNEP, United Nations Environment Programme; WU, Water Use.

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friendlier alternative in specific contexts, aligning with heightened environmental concerns and regulatory pressures surrounding plastic usage.

1. Introduction

Plastic waste pollution stands as one of the most pressing environmental emergencies of the 21st century (UNEP, 2021), posing escalating threats to biodiversity in marine and terrestrial ecosystems (Campanale et al., 2020), and jeopardizing human well-being (Prata et al., 2020). Annually, an estimated 8.3 million tonnes of mismanaged plastic waste end up in the oceans (Napper and Thompson, 2020), a figure projected to rise as global plastic production is anticipated to exceed 1100 million tonnes by 2050 (Geyer, 2020). The production, usage, and disposal of conventional fossil fuel-based plastics, including polyethylene, polypropylene, polystyrene, polyvinyl chloride and polyethylene terephthalate (Plastics Europe, 2021), are anticipated to contribute as much as 19 % of the global carbon budget by 2040 (UNEP, 2021). Today, there is actual a bioplastic alternative for almost every conventional plastic material and corresponding application, including bio-based non-biodegradable plastics, such as bio-PE and bio-PP, as well as biodegradable materials like polylactic acid (PLA) and polyhydroxyalkanoate (PHA) (Geueke et al., 2018).However, in some cases there are technical hurdles and controversies hinder large market uptake (Guillard et al., 2018).

Roughly 40 % of the total plastic production is allocated to packaging, with 60 % of this intended for food and beverage applications (Plastics Europe, 2021). Unfortunately, up to 99 % of these packages originate from fossil fuels or virgin feedstock (CIEL, 2019), and the vast majority are single-use items (UNEP, 2018). In response to this urgent issue (Kiessling et al., 2023), the European Union has implemented a series of action plans and regulatory frameworks, such as Directive (EU) No 2019/904, that aims to reduce the environmental impact of certain plastic products by prioritizing sustainable and non-toxic reusable products and reuse systems over single-use items (Directive (EU) 2019/904, 2019).

Food packaging plays a critical role in preserving food quality, ensuring safety, and facilitating distribution, marketing and consumption (Conseil National De L'emballage, 2022) thereby reducing food loss and waste (FLW) (Guillard et al., 2018). However, perishable products, such as fish or seafood, face challenges in maintaining quality throughout the supply chain due to biochemical and biological factors (Alam, 2007), resulting in a substantial 36 % FLW of edible seafood in Europe from landing to consumption (Almeida et al., 2021). Enhanced knowledge of the advantages and disadvantages of packaging in the distribution and export of fresh fish can optimize package selection, improve product quality and mitigate contamination and FLW (Meherishi et al., 2019). Expanded Polystyrene (EPS) stands as the predominant packaging material for transporting and storing fish within the fishing industry. However, it also ranks among the most prevalent contributors to marine litter that is found floating at sea or littering coastlines due to accidental losses at sea from fishing vessels, as well as mismanagement of waste and insufficient recycling infrastructure (WWF, 2024).

The evident importance of food packaging (Fogt Jacobsen et al., 2022), particularly for fish products, warrants an assessment of its environmental impacts, given its potential as a significant hotspot despite its short use phase (Abejón et al., 2020). Life Cycle Assessment (LCA) has proven to be the most comprehensive and adequate tool for such evaluations, offering decision-making criteria for producers and stakeholders (Barros et al., 2019). While LCA has been extensively applied to compare primary food and beverage packaging alternatives such as bread (Koskela et al., 2014), eggs (Zabaniotou and Kassidi, 2003), seafood (Laso et al., 2018; Almeida et al., 2023), olive oil (Navarro et al., 2018) or wine (Gazulla et al., 2010; Vázquez-Rowe et al., 2012), secondary and tertiary packaging remains less explored. Studies like Albrecht et al. (2018) and Abejón et al. (2020) examined distribution packaging for fruits and vegetables using single-use cardboard boxes and reusable plastic crates (RPC) and showed the potential of using reusable systems. Most recently, Kim et al. (2023) compared two reusable options for fresh food distribution in Korea: vacuum insulation panel (VIP) box made of r-PET, and EPE box; and a disposable EPS package; finding that reusable options had lower environmental burdens after fewer than 15 cycles.

LCA studies specifically comparing fish boxes have also been conducted, such as the analysis by the European Manufacturers of Expanded Polystyrene association (EUMEPS, 2011) and the research by Stora Enso Oyj (2018). They assessed boxes made of EPS on one hand, and of corrugated board (polypropylene and water-resistant) on the other hand. These studies highlighted the importance of packaging weight per quantity of fish transported and identified key stages in the life cycle contributing to environmental impacts: the production of raw materials and the processing of main packaging constituent. However, they concluded that no single packaging solution is preferable for all impact categories (EUMEPS, 2011). A most recent study by Hilmarsdottir et al. (2024) evaluated reusable tubs made of PE/PUR versus single-use EPS boxes for exporting fish from Iceland to Europe, concluding that multiuse tubs had lower environmental even during first year of usage.

Against this backdrop, the ultimate objective of this study is twofold: i) to compare the environmental performance of two alternative packaging solutions currently used for seafood distribution within Spain: EPS boxes and reusable plastic crates of high-density polyethylene (HDPE), in order to select the most suitable option from an environmental point of view and ii) to examine reasonable scenarios for environmental impact minimization at packaging level. Moreover, results are intended to serve as basis for suggesting improvement actions in a sector that is expected to undergo significant growth and shift in the next decade. The novelty of this study lies in addressing one of the main producers and distributors of fish and seafood products in the European Union, i.e., Spain. Unlike previous studies that focus on other sectors, packaging formats or distribution networks, this contribution addresses different short supply chain scenarios, with the objective of evaluating both the influence of transportation and packaging on environmental impacts by employing the most up-to-date and rigorous tools and methods.

2. Materials and methods

The LCA methodology was conducted based on the ISO 14040 (ISO 14040:2006/ Amd 1:2020) and ISO 14044 standards (ISO 14044:2006/ Amd 2:2020) This approach enables the analysis of the environmental burdens associated with each stage of the packaging life cycle, from the extraction of resources and the processing of raw materials to the final recycling and disposal of the remaining waste.

2.1. Goal and scope

This study aimed to bring forward a thorough quantification of the environmental impacts linked to fish and seafood distribution in Northwest Spain (Vigo, Galicia) using two plastic packaging solutions: reusable plastic crates (RPC) and single-use EPS boxes. The formers are usually made of virgin plastics such as high-density polyethylene (HDPE). They stand out for their remarkable resistance, high quality and wide variety of sizes and designs, with stackable and nestable options seemingly the most promising for space-saving in the backhauling. On the other side, the latter are widely used due to their extremely lightweight characteristics (they are 98 % air) and excellent resistance to thermal shock, thus perfectly maintaining the cold chain (Plastics Europe, 2024). The main difference between them is their shelf life. Whereas plastic crates are designed for multiple uses undergoing collection, inspection, washing and subsequently re-distribution until they no longer meet food quality standards, single-use crates are intended for one-time use. Once their purpose is fulfilled, they are managed as recyclable plastic waste.

According to the latest statistics from one of the leading manufacturers, the use of RPC reduces the number of single-use packs per year by 50–120 units (TEPSA, 2023). Increasingly restrictive directives on single-use and recycling of packaging are compromising the use of non-reusable options, so this study will provide science-based information on the real impacts of plastic packaging alternatives.

2.2. Function and functional unit

The function of the system was to distribute fresh fish or seafood from the Port of Vigo to fish markets and retailers. Consequently, the selected functional unit (FU), i.e., the quantifiable reference to which material and energy input/output flows are linked, was set as the capacity of a specific container to repeatedly transport a certain amount of food as sustainably as possible. Hence, initially the outset FU was defined as the carriage of 1000 t of seafood products in the distinct plastic packages in northern Spain. The selection of a mass-based FU is consistent with the earlier LCA studies (EUMEPS, 2011) and was selected so that results are scaled to quantities that are familiar from everyday interactions. In order to translate this FU into reference flows of boxes and crates, the loading weight of the packages has been considered: EPS boxes and RPC can carry 8 kg and 12 kg of product, respectively. However, it must be taken into account that not all the capacity of the box is intended to contain fish, but a percentage is filled with ice. In the case of EPS boxes, the ice content does not exceed 20 %, i.e., 1.6 kg, whereas plastic crates contain 2 kg of ice, according to the industrial manufacturers. In addition, RPC have an average lifespan of 10.5 years and are reused in 120 rotations per year. Consequently, this means that over the 10.5 years of the crate's useful lifetime, they could have around 1260 fillings per unit. Moreover, it is necessary to include in the analysis the number of plastic crates that break and/or need to be repaired or replaced by new packages to continue to fulfil their function. According to the manufacturer this number does not exceed 1 %. Thus, to compensate the effects of the rotations, the outset FU was redefined as the distribution of 1260,000 t of fish in the two alternative packages. This meant that 196,875,000 EPS and 101,000 RPC packaging units were needed to transport the new total amount of seafood. Table SM1 in the Supplementary Material (SM) file furnishes a comprehensive overview of the flow calculations.

The input data for the manufacturing, use and end-of-life of the two solutions analyzed are detailed in Fig. 1, representing the reference flows in each case.

2.3. System boundaries

In this study the whole life cycle of both distribution systems was encompassed. Therefore, the LCA included the stages of raw materials extraction for the manufacture of the package, the distribution to the customer and the period of use, as well as the final end-of-life (EoL) management routes. The limits also covered ancillary systems, such as transport routes of raw materials for manufacture the packages, the obtention of electricity from primary energy sources, and the extraction and burning of fuel for the transport of packages and waste. Notwithstanding, the production of capital goods remained outside the boundaries of the proposed system. Since experience indicated that the environmental impacts of these components are negligible in relation to those arising from the function of the plant (Frischknecht et al., 2007), this hypothesis was justified in the scope of this work. The supply (wild catch) and production of the fish together with the diesel consumption directly related to their transport, was not included in the limits as these steps are independent of the type of procurement packaging chosen. At the production phase, each packaging solution involves inputs and outputs of materials and energy, which are detailed in the systems description section. Regarding the transport of packages to the port, the distance from each production plant is considered.

2.4. System description and life cycle inventory

This section gathers all the information related to the two systems evaluated. Table 1 gives an overview of the specifications of each packaging. The data on manufacture, transformation, distribution, backhauling logistics and EoL steps were collected from various packaging industrial companies with high representativeness in the northwest of Spain (companies names are not disclosed for confidentiality reasons). The inventory data correspond to the productions of the years 2021–2022 (Table 2). An assessment of data quality can be found in table SM6 of the SM file.

2.4.1. Manufacture (production stage)

2.4.1.1. Manufacture of EPS boxes. EPS is obtained from the transformation of expandable polystyrene (PS). This raw material is a polymer of styrene containing a blowing agent, pentane. The process of transforming the raw material (PS) into finished articles made of EPS is essentially a three-stage cycle: i) pre-expansion, ii) intermediate resting

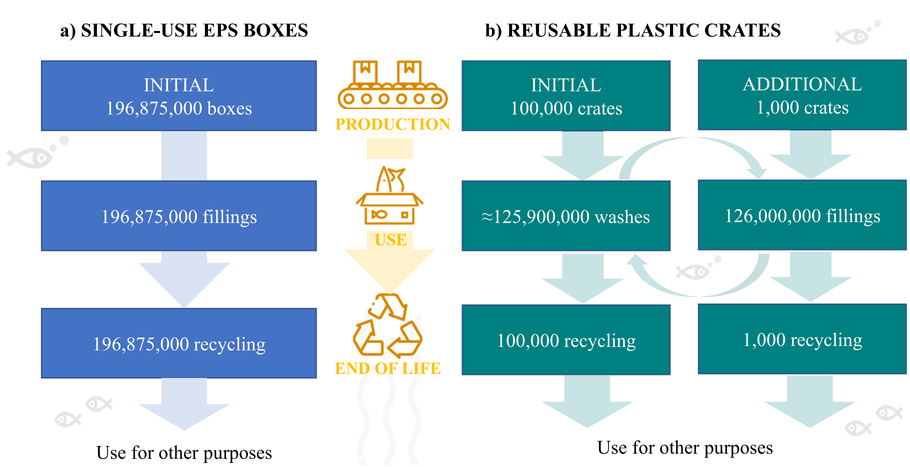
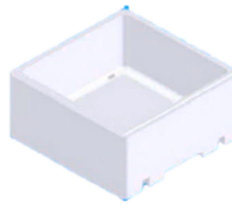


Fig. 1. Overview of system characteristics and flows over the life cycle for a) single-use EPS boxes and b) reusable plastic crates.

Table 1
Main characteristics and key properties of the two evaluated packaging options. Data refer to 1 unit of packaging.

	Single-use EPS boxes	Reusable plastic crates (RPC)
		
Outer Dimensions (cm)	40 × 40 × 13	60 × 40 × 13
Weight (kg)	0.203	1.2
Capacity (L)	14.2	20
Capacity (kg)	8	12
Fish (kg)	6.4	10
Ice (kg)	1.6	2
Lid	40 × 40 × 2	No
Lid weight (kg)	0.071	–
Composition	Expanded polystyrene (EPS)	High density polyethylene (HDPE)
Useful life	Single use	Reusable (10.5 years on average)
Rotations per year	–	120
Properties*	Stackable	Stackable, nestable

* Packaging suitable for contact with foodstuffs. The products used in the manufacture of boxes and lids comply with current legislation on plastics in contact with foodstuffs (Regulation (EU) N^0 2020/1245, Regulation (EC) N^0 2023/2006 and Regulation (EC) N^0 1935/2004).

Table 2
Life cycle inventories for the two seafood packaging solutions compared. Input and output flows refer to 1 packaging unit. Ecoinvent dataset used in the modelling are compiled in Table SM5 of the SM file.

	EPS	RPC
Manufacture		
Expandable polystyrene (kg)	$3.00 \cdot 10^{-3}$	
Transport of expandable polystyrene (km)	4000	
Petroleum (kg)		1.17
Transport of petroleum (km)		500
Additives: colouring agents (kg)		$2.40 \cdot 10^{-2}$
Transport of additives (km)		500
Electricity (kWh)	$1.10 \cdot 10^{-1}$	$3.10 \cdot 10^{-1}$
Steam (L)	$2.00 \cdot 10^{-2}$	29
Distribution to harbour		
Plastic bags (kg)	$6.00 \cdot 10^{-3}$	
Plastic film (g)		$2.40 \cdot 10^{-2}$
Pallets (p)		$3.00 \cdot 10^{-3}$
Transport to harbour (km)	145	215
Filling and distribution from harbour to markets		
Ice (kg)	1.60	2
Fish (kg)	6.40	10
Distribution scenarios		
1. *Local (from harbour to local fish market) (km)*	19.70	19.70
2. *Regional (from harbour to principal regional markets) (km)*	94.40	94.40
3. *National (from harbour to national wholesale market) (km)*	610	610
Backhauling from consumers to reuse or revalorization, and end of life (EoL) management		
Washing and disinfection process		
Water (kg)		1.20
Electricity (kWh)		0.29
Detergent (kg)		$1.00 \cdot 10^{-3}$
Transport of detergent (km)		3000
Recycling process		
Electricity (kWh)	$2.00 \cdot 10^{-3}$	$2.2 \cdot 10^{-2}$

and stabilisation, and iii) expansion and final moulding.

Data gathered for the production of PS beads were extracted from the Ecoinvent v3.10 database (Ecoinvent, 2024) implemented in Simapro 9.5 software (PRé Sustainability, 2024).

2.4.1.2. Manufacture of plastic crates. HDPE, made from crude oil, derives its main monomer, ethylene, from a naphtha or diesel cracking process in a steam cracker. The impact of oil extraction and refining was included in the inventory data for HDPE production collected from the Ecoinvent v3.10 database (Ecoinvent, 2024) implemented in the Simapro 9.5 software (PRé Sustainability, 2024). The RPC are manufactured through a plastic injection moulding process in which HDPE granules, obtained commercially, are melted. During the process the same grams as box weight are consumed, with a small amount of loss occurring in the casting (injection line), which is negligible in overall production terms. That is, for a 1.0 kg box, 1.0 kg of HDPE pellets are injected. Any residue on the surface of the mould can be re-melted and reused. In general, pure plastic granules are not stable against sunlight, heat and other external agents. For this reason, it is necessary to add certain additives in their composition. For the concerning case of RPC used for fish transport, the manufacturer adds 2 % of masterbach. These commercial green pigments are characterized by chemical formulations based on chromium oxide pigments with excellent resistance properties - heat resistance, resistance to migration, light and weathering. The commercial pigments used contain low concentrations of chromium (VI) which allows their use as colouring in food packaging in compliance with European regulations (UE) 2020/1245 of 2 September 2020 and Correcting Regulation (EU) No 10/2011 on Plastic Materials and Articles Intended to come into Contact with Food (COMMISSION, 2020).

2.4.2. Use (service life stage)

2.4.2.1. Distribution from producers to harbour. The EPS boxes including lid are delivered in trucks from the factory to the harbour (an average distance of 145 km) in closed plastic bags with a capacity of 16 units.

The nestable plastic crates are packed with film and distributed on pallets with occupancy of 304 units. To fill a truck, 33 pallets are necessary, so each truck carries 10,032 empty units. The distance between the factory and the harbour is estimated at 215 km. RPC are delivered directly on the ship or to the exporter in an efficient way, well established in the fishing sector. *Re*-packing is eliminated, sending the crate with landed fish straightly to the point of sale without any handling, which guarantees its freshness and original appearance until it reaches the final consumer (TEPSA, 2023).

2.4.2.2. Distribution from harbour to markets. Once the boxes and crates are filled with fish and ice, they are distributed in refrigerated trucks to the different points of sale. Different scenarios for fish distribution to points of sale were also created to assess the contribution of fish transport to the total environmental impacts of the system: i) local, ii) regional and iii) national distribution routes of fish from the port of Vigo (Fig. 2).

i) Local distribution: the fish is landed directly in the surroundings of the fish auction, so transport was considered insignificant. From this point, fish is also delivered to the most important markets in the city: Plaza de Abastos de Bouzas and the markets of Travesas, O Calvario, Progreso, Berbés and Teis; making up a 19.7 km delivery route.
ii) Regional distribution: this scenario considered the supply of fish in the municipal market of Pontevedra and in the main market of Santiago de Compostela, with a total distance of 94.4 km from the port of Vigo.
iii) National distribution: Finally, to simulate a national trade, a transport to Mercamadrid, the main wholesale market for fresh products in Spain located 610 km away, was considered.

2.4.3. Backhauling from consumers to reuse or revalorization

Once the EPS boxes have been single-used, they are collected by the same company and returned to their facilities to be recycled. In the alternative scenario, plastic crates are recovered from the market and, undergoing a rigorous washing and disinfection protocol, they are reintroduced back into the circuit. The reconditioning procedure takes place within the same facilities, housing two dedicated washing tunnels where the cases are exposed to a sequence of treatments involving hot water (55 °C), specialized detergents, and chlorine. All these compounds are sanitary and undergo an exhaustive quality control due to their use in food-grade containers. The wastewater stemming from this process is treated in their own wastewater treatment plant equipped with an advance grease separation system and filters designed to capture organic matter and detergents effectively. According to data provided by the manufacturer, the proportion of crates that find their way back to the facility for washing varies, though it is conservatively estimated to hover around 20 %. It is worth noting that the remaining 80 % undergoes direct management at the port. This percentage serves as a dynamic parameter scrutinized in the sensitivity analysis by systematically modifying the proportion of containers submitted to factory washing (refer to section 2.7).

2.4.4. End of life management (Recycling and valorization)

The EPS manufacture plant has an eco-recycling area where used boxes are completely compacted and crushed to give them a new life as urban furniture, or marshes in ports.

Regarding plastic crates, once they are no longer reusable as they do not meet the quality standards to be repaired and reused, they are 100 % recyclable in the production plant and the material obtained is usually used to manufacture different by-products for the plastic pipe sector. Recent studies suggest that recycled materials obtained from combinations of EPS (expanded polystyrene) and plastics, such as PP (polypropylene), have the potential to serve as viable alternatives to conventional materials like PVC (polyvinyl chloride). These mixtures offer the prospect of mitigating environmental impacts while maintaining comparable strength properties to those found in traditional construction materials (Bautista et al., 2023).

2.5. Life cycle impact assessment

SimaPro 9.5 software (PRé Sustainability, 2024) was used to compute the Life Cycle Impact Assessment (LCIA) phase, in which material and energy flows aggregated in the LCI are translated into environmental impact results through the use of characterization factors. The selected method was Environmental Footprint EF 3.1 (adapted) (European Commission, 2018) and a total of six conventional impact midpoint categories were analyzed (Table 2): Climate change (CC), Acidification (AC), Eutrophication—freshwater (EUF), Eutrophication—marine (EUM), Water use (WU), Resource use—fossils (RUF). This method was chosen since it provides a higher degree of specificity and consistency than other methods (Sanyé-Mengual et al., 2022), as well as

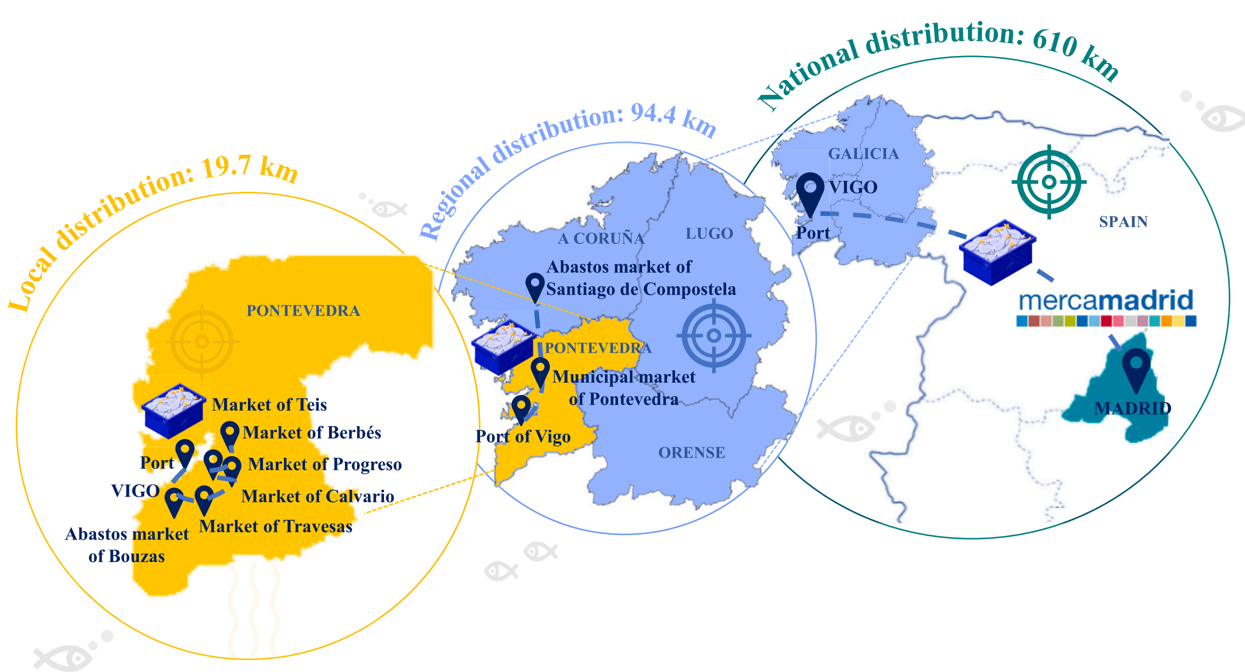


Fig. 2. Map of the different routes of distribution considered: i) local, ii) regional and iii) national distribution routes of fish from the port of Vigo.

being suggested by the European Commission for comparison and improvement of the environmental performance of products and companies. The indicators included are the commonly used in LCA studies of packaging (Albrecht et al., 2013; Del Borghi et al., 2021). They comprehensively address environmental impacts across different protection areas, offering a holistic view of product sustainability. Special attention is given to the degradation of aquifer ecosystems, fossil resources utilization in manufacturing, and emissions generated throughout the product's life cycle. In addition, the supplementary material includes the results for all the indicators included in the Environmental Footprint 3.1 (adapted) V1.01 method (Table SM7).

2.6. Data, limitations, assumptions, and hypotheses

This section contains all the decisions taken for the study and, for ease of follow-up, they have been grouped into the life cycle phases of the elements assessed.

2.6.1. Raw materials and processing

The virgin material for EPS boxes and RPC production comes from the international market (France or Austria) mainly because of its price/quality ratio. It is transported to Galicia (Northwest of Spain) by road in trucks, so an average distance of 4000 km was considered. The consumption of electric energy to produce the packages was assessed from the representative Spanish country-specific residual electricity mix for 2021 (AIB, 2023).

2.6.2. Distribution from factory to ports

European wooden pallets with a weight of 8 kg have been considered for the distribution of plastic crates from factory to port. The data pertaining to the utilization of film for crate transportation from the factory to the harbour was sourced from the research conducted by Abejón et al. (2020), and its accuracy was verified through experimental data.

2.6.3. Filling and distribution to markets

An energy consumption of 630 MJ/t was assumed for ice production, based on a Galician port authority as reference (Ceballos-Santos et al., 2023). In both cases, the mass load of fish in each package is assumed, considering inshore species that do not present special characteristics of delicacy that limit the filling of the boxes and crates. In addition, establishing a definitive connection between the thermal insulation parameters of the boxes and the energy required for refrigerating the trucks proved to be unattainable during the course of the present study. This energy requirement was held as constant, regardless of the chosen packaging solution. Integrating this particular factor in the results would likely strengthen the case for favoring EPS packaging. The transportation to all markets has been simulated using a standard medium freight lorry sourced from the Ecoinvent v3.10 database. It's worth noting that this may present a limitation, as distribution to local and national markets often involves trucks with varying characteristics.

2.6.4. Washing stage

In the evaluation of the cleaning stage within the life cycle of the RPCs, the operational parameters of the washing tunnel were considered to be active for 12 h each day, with a designated energy consumption of 110 kWh (primary data from factory).

Allocation factors were implemented to partition the resource consumption within the washing stage, encompassing elements such as water, electricity, and detergent. This resource consumption data was collected on a monthly basis. According to information provided by the RPC and EPS manufacturers, the specific containers being examined roughly constitutes 50 % of the total production. Building on this, it was deduced that half of the overall monthly consumption of resources in washing should be attributed to this particular type of crates.

2.6.5. Recycling and end-of-life

During the EoL stage, the management of packaging as waste brings out secondary recycled materials to be reused in other products or systems, which implies the incorporation of new additional functions to the distribution system. Consistently, for both systems to be equivalent, the environmental impacts related to each function must be allocated to consider exclusively the part covering the principal function shared by the two systems. Setting this allocation would imply a quite complex procedure, but fortunately it can be avoided performing a system expansion, that means subtracting the environmental negative effects associated with the procurement of materials and energy from alternative production sources. A schematic view of the initial and expanded system boundaries can be seen in Fig. 3.

Electricity consumption estimated for the HDPE crates recycling process within the compacting machine were determined based on standard commercial specifications. Industrial compactors were selected as the focal point, boasting a dynamic power range of approximately 110–120 kW/h with the capability to process 1000 kg/h of plastic material. On the other hand, flows of 3000 kg/h of plastic were processed in units with an energy consumption range of 260–300 kWh/h. In the context of the recycling of used EPS and HDPE in an open loop system, the underlying assumption was that for every 1 kg of recycled material, an equivalent of 1 kg of virgin material is replaced, which is ultimately used for alternative purposes. This approach has been taken as a simplification; however, it is important to acknowledge that material losses are common in recycling processes. Additionally, considering the degradation of plastic quality is crucial. The exclusion of these factors should be viewed as a limitation and should be addressed in future research efforts.

2.7. Sensitivity analysis

A sensitivity analysis was conducted for different RPC cleaning approaches. Firstly, it was varied the percentage of crates washed at the manufacturing plant, ranging from 0 % (indicating that all crates are cleaned at the port facility) to 100 % (implying that all crates are returned to the factory for cleaning). Additionally, as base case, an intermediate value of 20 % was considered, which is deemed to be the

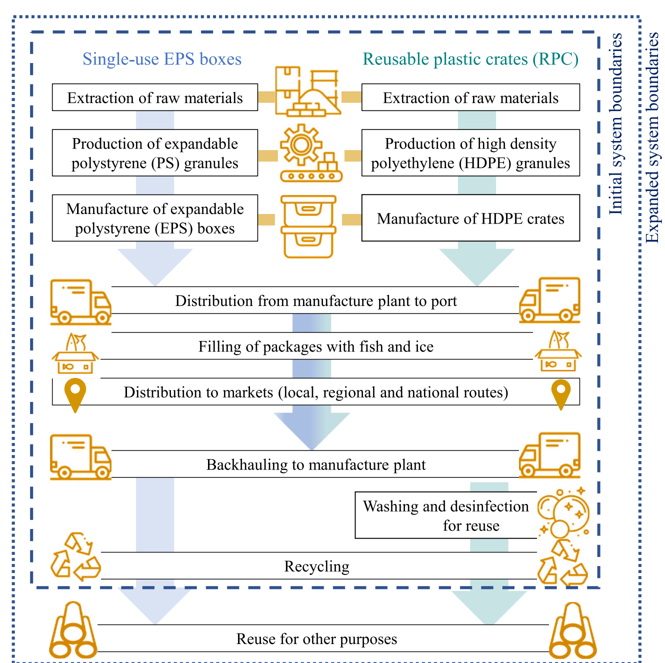


Fig. 3. Schematic overview of the boundaries of the initial and expanded systems.

most realistic scenario based on inputs from certain manufacturers. These estimates suggest that approximately 80 % to 90 % of containers are typically conditioned directly at the ports.

To quantify the environmental improvements or differences, Eq. 1 was applied, using the 20 % return rate as the baseline case. This choice allows us to evaluate the potential environmental impacts in a practical setting, reflecting current industry practices and trends.

$$\Delta IA = \frac{IAM - IAB}{IAB} \cdot 100 \quad (1)$$

where ΔIA represents the change in environmental impact, IAM denotes the environmental impact with the modified parameter, and IAB corresponds to the environmental impact of the baseline scenario. It is essential to understand that a positive value for ΔIA indicates that the option being analyzed has a greater environmental impact than the baseline scenario. Conversely, a negative value implies that the modified option has a reduced environmental impact compared to the baseline scenario. By examining these different scenarios, it can be effectively assessed and compared the environmental implications of different options, gaining valuable insights and facilitating informed decision-making towards the most effective and sustainable management strategies.

3. Results and discussion

3.1. Life cycle impact assessment

3.1.1. Baseline case and distribution scenarios

This section unveils the outcomes pertaining to the baseline case, which involves a 20 % return of RPCs to the factory for washing. To enhance the graphical representation, the life cycle stages have been grouped as follows: i) production, involving the fabrication of the packaging solutions, ii) distribution to port, including the transport of crates from the factory to the port, as well as the return of used crates from the market to the port, iii) market delivery routes (i.e., local, regional and national trade), iv) backhauling of empty containers to factory, and v) washing process for RPCs, vi) recycling of single-used EPS boxes and non-operational HDPE crates.

Focusing on Fig. 4, which portrays the results obtained for the CC impact category, it can be observed that the total values for local and regional trade are similar for both packaging alternatives: $5.02 \cdot 10^7$ (RPCs) and $4.87 \cdot 10^7$ (EPS boxes) kg CO_2 eq. per FU, and $1.20 \cdot 10^8$ (RPCs) and $1.19 \cdot 10^8$ (EPS boxes) kg CO_2 eq. per FU, correspondingly. Moving to national distribution, a discernible divergence emerges, with RPC reaching $6.04 \cdot 10^8$ kg CO_2 eq. per FU, marking a 11.85 % increase compared to EPS boxes. These results seem to be higher than those reported by Abejón et al. (2020) as they calculated a total of $1.64 \cdot 10^6$ kg CO_2 eq. per FU (considering $6.6 \cdot 10^7$ RPC units in an average 400 km for vegetables transport).

Upon a more comprehensive examination of the results, it could be determined that the distribution of filled packages to markets emerged as the major hotspot for the two containers, spanning all three scenarios under evaluation. This stage constituted approximately 52 % of the total CC impact for local delivery, a substantial 80 % for regional transport, and a staggering 96 % for the national trade. This result is function of two key parameters: the load to be transported (in kilogrammes) and the distance covered (in kilometers). Across all assessed scenarios, the distance remains uniform, making the weight of each system the critical variable. At this juncture, the mass of the package plays a fundamental role, representing a crucial advantage for EPS boxes due to their remarkable lightweight nature; they tip the scales at a mere 0.20 kg, a stark contrast to the 1.20 kg attributed to an RPC. Furthermore, it is imperative to take into consideration the volume of seafood and ice accommodated within each packaging solution.

Comparing these results with the literature is challenging due to the varying functional units and formats used in different studies. Therefore, it is most prudent to focus on discussing the general trends observed. The significance of packaging weight per quantity of transported fish mirrored the insights presented in the EUMEPS report (EUMEPS, 2011). In this document it was also recommended that any weight reduction

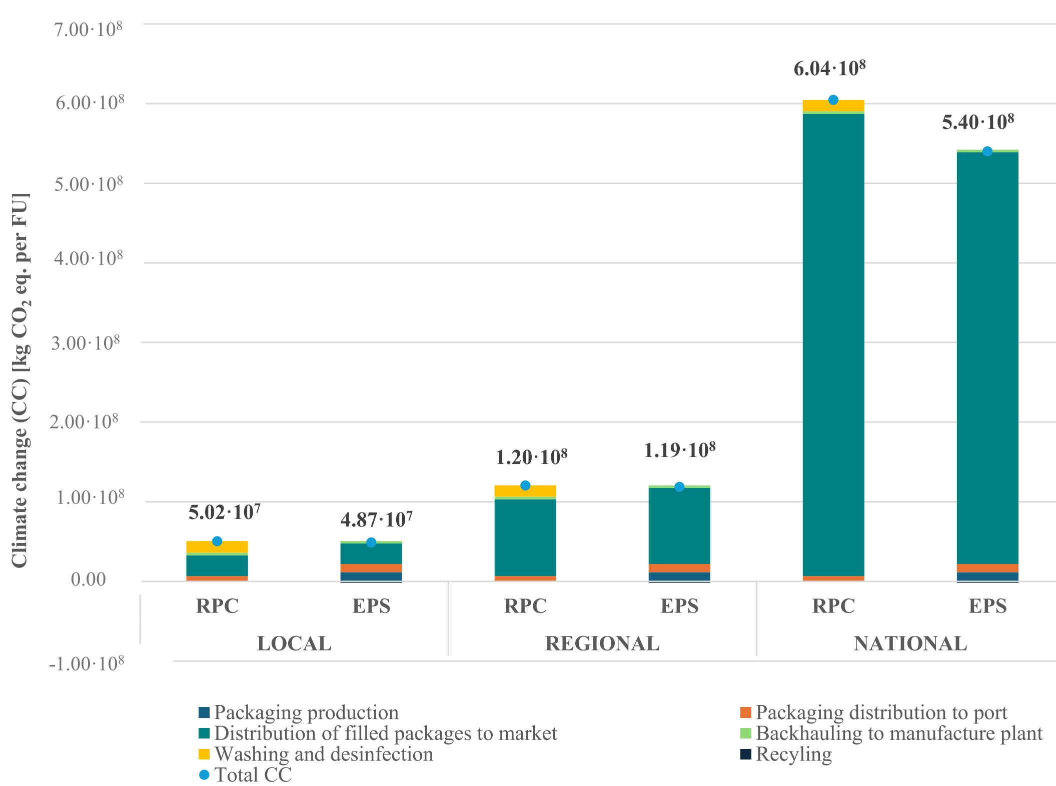


Fig. 4. Climate change results for reusable plastic crates (RPC) and single-use EPS boxes for the different distribution scenarios assessed.

efforts, without altering the box's characteristics, can indeed have a substantial impact on the overall outcome. In a similar vein, the research conducted by Stora Enso Oyj (2018) underscored significant disparities attributed to package weight when comparing the environmental burdens of 10 kg and 20 kg containers made of EPS and with their commercial counterpart, EcoFishBox™.

Most recently, Hilmarsdottir et al. (2024) also pushed the weight of the raw plastic materials and size of the tubs as key factors affecting the environmental impacts for transport.

On another note, it was worth emphasizing that the washing process constituted 28 % of the total CC impact for RPCs, while the production of EPS boxes contributed to 23 % of the CC result in the context of the local scenario. Notably, the remaining stages exhibited relatively modest contributions, most staying below the 20 % threshold. Regarding the recycling process of non-functional packaging, environmental benefits were computed across all scenarios, being more pronounced in the case of EPS box management, which resulted in a noteworthy reduction in burden by $-1.94{\cdot}10^6$ kg CO_2 eq per FU.

After a thorough examination of the CC results, Fig. 5 broadens its purview to encompass the complete spectrum of impact categories scrutinized in this study across local (Fig. 5 a), regional (Fig. 5 b), and national (Fig. 5 c) distribution scenarios. For a comprehensive view of the results, the author should refer to Tables SM2-SM4 in the SM, which presents the compiled impact indicators for all evaluated scenarios. Table SM7 compiles the results per packaging unit for all the rest of indicators included in the EF3.1 method. A key discovery resonated with the findings of the climate change analysis. Specifically, a shared focal point emerged across all scenarios and both packaging alternatives: the distribution-to-markets stage stood out as a consistent hotspot. This pattern observed in the context of CC impact scenarios remained consistent across the spectrum of other impact indicators as well. The significance of this distribution stage's role varies across the indicators, ranging from 46 % for the EUF indicator in HDPE crates for local distribution (Fig. 5 a), to an impressive >95 % in three —CC, AC, EUM— out of the six impact categories analyzed within the national distribution scenario (Fig. 5 c), irrespective of the type of container. These findings seem to elucidate that the emissions from the production and consumption of fuel for transport carry burdens to different environmental domains, from water degradation to the depletion of fossil resources.

It is important to recall that the sole distinction among scenarios lay in the distance traversed by the trucks during the distribution to markets. Hence, Fig. 5 vividly illustrates the notable increase in the contribution of this transportation stage, consequently resulting in a reduction of the share for the other life-cycle stages.

These findings are consistent with the results reported by Stora Enso Oyj (2018). In this study, the transportation of loaded packages, particularly for larger containers like the 20 kg ones, emerged as one of the most relevant life cycle phases in many environmental aspects. This transportation process was responsible for 23–60 % of the total CC burden for corrugated board packaging and 7–30 % for EPS packaging, depending on the distance the packages had to be transported.

With the extension of delivery distances, the contrast between the two container options becomes increasingly conspicuous, favoring EPS boxes. This divergence arises, as abovementioned, from their low pitch and capacity. Despite plastic crates being nine times heavier, they manage to accommodate 56 % more fish. Thus, a trade-off in environmental impact results emerges due to the product of load and distance (used for the modelling), along with the number of boxes required to fulfil the function of the system.

The manufacturing process contributed significantly more to the overall impacts for EPS boxes (20 % on average across all categories), primarily owing to their single-use nature, which mandated the production of 196,875,000 units—an increase of over 194 thousand percent in comparison with RPCs. Furthermore, the most substantial impacts were observed in relation to RUF ($2.84{\cdot}10^8$ MJ per FU) and the CC ($1.14{\cdot}10^7$ kg CO_2 eq per FU) metrics. Electricity consumption was the primary driver of the significant impacts.

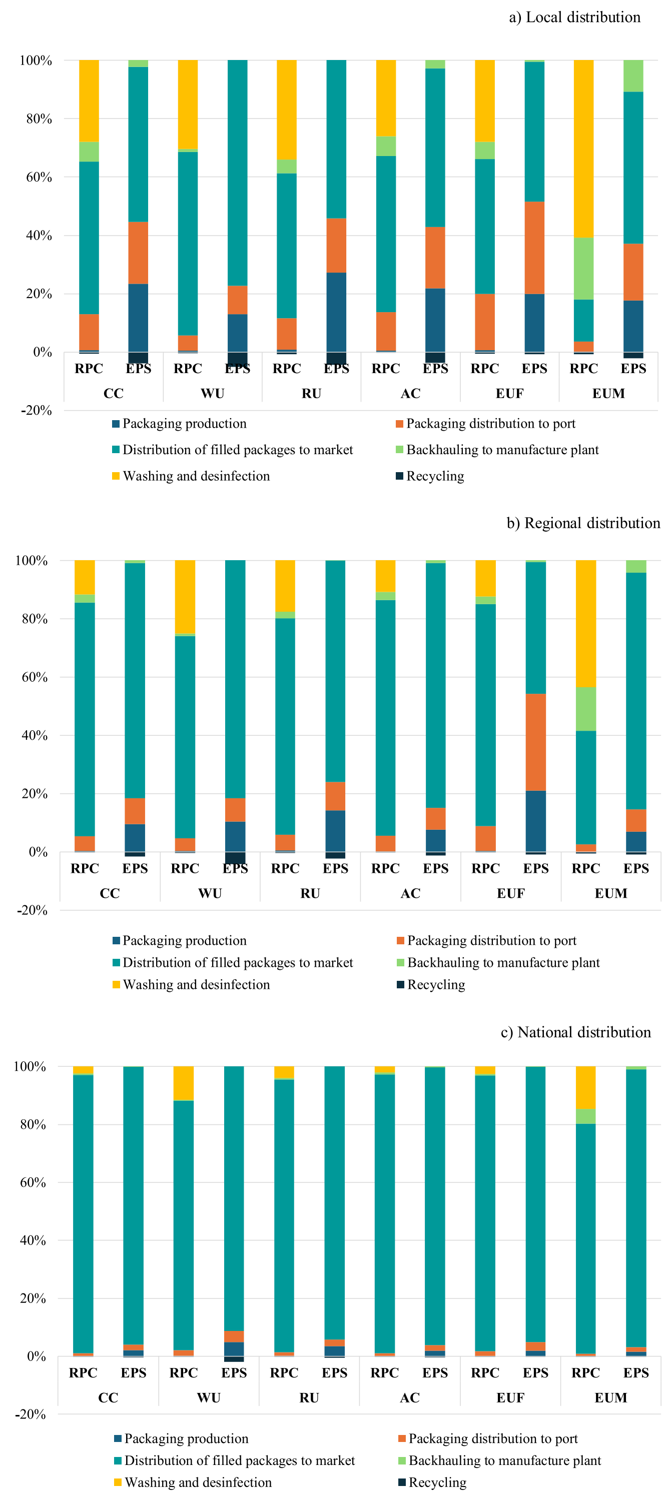


Fig. 5. Relative contributions of each life cycle stage to the environmental indicators in the a) local, b) regional and c) national distributions, for the two packaging solutions.

Regarding the washing process, only applicable to RPCs, its significance becomes more pronounced in the context of marine eutrophication and fossil resource consumption categories, reaching values of $1.12{\cdot}10^5$ kg N eq. and $3.79{\cdot}10^8$ MJ, per FU respectively. Following closely was the WU category with $1.05{\cdot}10^7$ m^3 deprived, and CC category registering at a $1.35{\cdot}10^7$ kg CO_2 eq per FU. These impacts stem from the considerable electricity consumption in the washing tunnels to ensure efficient disinfection and cleaning processes.

When it comes to recycling advantages, EPS boxes also demonstrated greater benefits, i.e. avoided loads represented as negative contributions in Fig. 5, per FU in terms of WU, CC, RU and AC.

Lastly, when considering the distribution of packages from the factory to the port, the collective impact distribution converged at an average of 16 % for all metrics across both packaging alternatives, both in the baseline scenario and during local distribution. These percentages exhibited a reduction during regional distribution (9 %) and further diminished during national distribution (2 %). In contrast, the distribution to the factory in the backhauling demonstrated a markedly lower influence of the total impacts during local transport. This impact dwindled to a mere 1 % during national trade, maintaining a consistent distribution pattern across most performance indicators.

This comprehensive analysis of delivery route scenarios underscores the paramount importance of distance optimization, since a marginal variance of a few kilometers could yield substantial long-term environmental burdens. Beyond the environmental implications, these deviations bear a pronounced effect on the economic landscape, particularly given the noteworthy fuel consumption exhibited by these delivery trucks. According to information provided by companies, this consumption can range from 30 to 40 l of fuel per 100 km. Adding complexity to this matter, these consumption patterns are further compounded by the erratic fluctuations in fuel prices, which have been particularly pronounced during recent periods characterized by economic turbulence, health emergencies and geopolitical crises. Exercise caution when interpreting the presented results, as the limitations of the modelling choices and the inherent uncertainties in the inventory data should not be overlooked.

3.2. Sensitivity analysis

A comprehensive sensitivity analysis was undertaken to explore the nuanced impact of varying washing locations on the overall life cycle impacts of reusable plastic crates used in the distribution of seafood. Results for the CC indicator was exclusively showcased in the sensitivity analysis due to the comparable performance observed across the remaining impact category indicators.

Fig. 6 displays the total kg of CO_2 eq. emitted per FU across the entire range of distances covered, spanning from local to national distributions. The graphical representation employed navy blue lines and dots to delineate the impact of EPS boxes, whereas the dark green counterparts

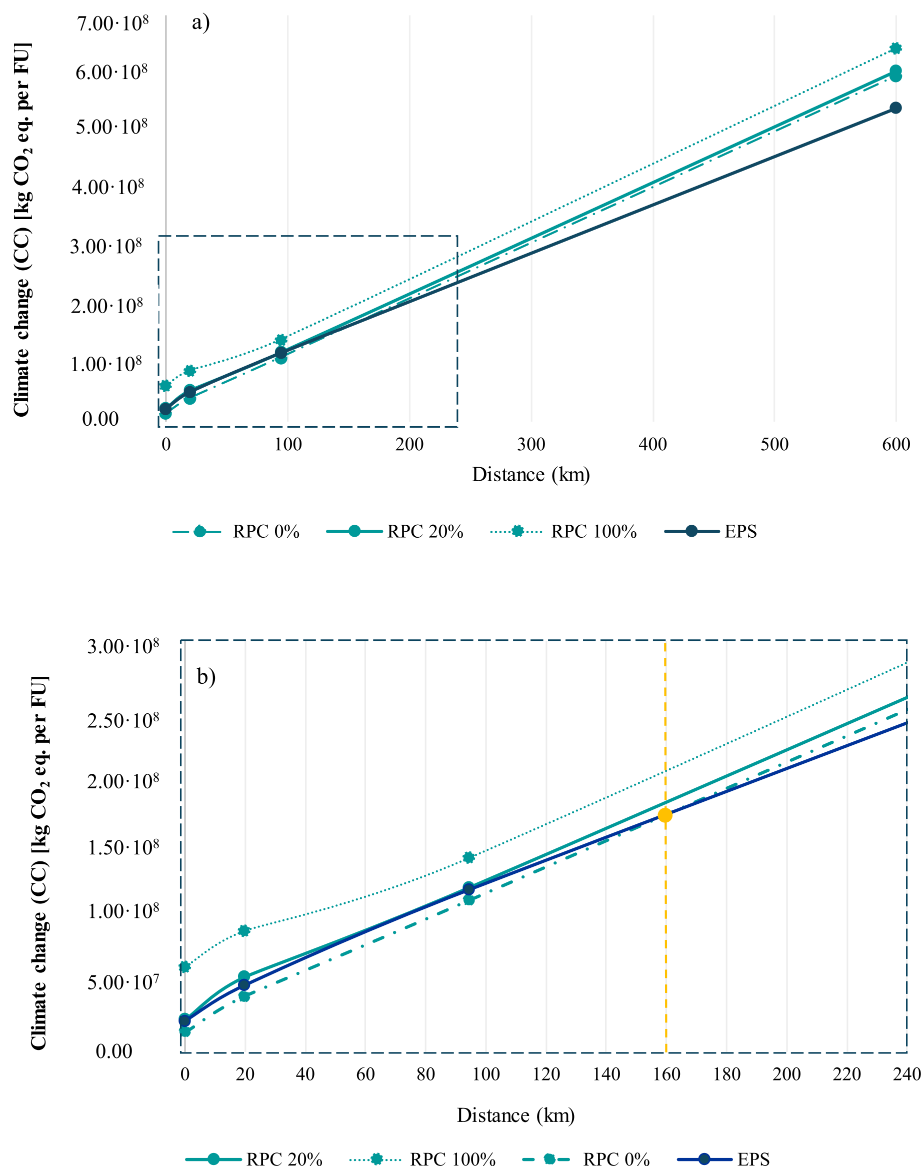


Fig. 6. Climate change results for the sensitivity analysis varying the washing location of the RPCs.

portray the three distinct alternatives for managing RPCs' washing process at varying factory percentages. As evident from the data, the heaviest burdens were recorded in instances where complete washing took place at the factory. Secondly, it could be observed that the baseline case (20 % washing at the factory) and the extreme scenario of complete washing at the port (0 % washing at the factory) yielded remarkably similar outcomes, both significantly below the preceding case. In addition, it seemed to be evident that the environmental impact values for EPS boxes remained notably lower than those for RPCs, a difference that amplified with increasing distances. Interestingly, this trend exhibited a reversal within shorter distances. To delve into this phenomenon more closely, a focused examination was conducted, zooming in on the **first** 240 km of the distribution range (Fig. 6 b). This amplified picture revealed that for distances closer than 160 km PRCs exhibited lower CC impacts when subjected to complete washing at the port. This configuration emerged as the optimal solution for the distribution of seafood within this distance range. However, beyond this inflection point, the environmental dynamics shifted, and the balance tipped in favor of EPS boxes. It was noteworthy that reducing the weight of the HDPE crates presented an opportunity to extend the distance they can travel while maintaining the same CC associated with transport. As explained above, this impact depends primarily on the parameters of weight (kg) and distance (km). This adjustment could result in favorable outcomes for reusable packaging when addressing regulatory restrictions for single-use containers. This finding was consistent with several research studies that state that optimal reusability occurs when long-distance transport and washing are minimized, a high number of rotations are assured (Accorsi et al., 2022), and both companies and consumers can avoid the need for additional parallel setups or unnecessary complexities in the supply chain (McKinsey's Materials Practice, 2023). Another realm ripe for optimisation was the crate washing process, which demanded substantial power and lead to a monthly energy consumption of approximately 30,000 kW.

To sum up, a comparative environmental analysis was performed to determine the optimal choice. Table 3 compiles the results of the sensitivity analysis for the different scenarios evaluated, using the chosen impact indicators, highlighting which of the two options, i.e., single-use EPS boxes and reusable plastic crates, was the best alternative in each situation, with a 10 % confidence degree. This margin accounted for potential uncertainties in the inventory data, ensuring a robust assessment of the environmental impact for each impact category.

As observed in Table 4, in the baseline scenario, both packaging solutions showed comparable suitability for local and regional distributions for five and three impact categories, respectively. Nevertheless, when it came to national trade, EPS boxes emerged as preferred choice across all impact categories… Conversely, in the scenario involving full factory washing, EPS boxes consistently proved to be the superior option across all indicators for regional and national trade. On the opposite, when considering complete washing at the port, RPCs exhibited better performance for local distributions in four out of six metrics. In the regional scenario, both options performed similarly, except for eutrophication issues; and EPS boxes continued to display a stronger environmental impacts in national transport.

The logistical intricacies of implementing a large-scale returnable packaging system, encompassing the national distribution network, require careful consideration. Effective planning and monitoring of the backhauling system are essential. One of the primary challenges lies in ensuring the traceability of the crates to prevent them from becoming lost or exiting the system, thereby contributing to mismanaged waste.

Table 3
Impact categories from EF 3.1 (adapted) method analyzed in this study.

Impact category	Units
Climate change (CC)	Kg CO_2 eq.
Acidification (AC)	mol H^+ eq.
Eutrophication—freshwater (EUF)	kg P eq
Eutrophication— marine (EUM)	kg N eq
Water use (WU)	m3 depriv.
Resource use—fossils (RUF)	MJ

4. Conclusions

This study assesses the environmental impacts associated with short supply distribution networks of seafood in Spain, considering national, regional and local scenarios and employing two different packaging alternatives: reusable plastic crates and single use EPS boxes. Based on a set of six impact categories, results slightly differ from those reported in literature for fresh plant-based products: in this case, the main hotspot was identified in the transportation stage, especially during the distribution from port to retailers, not in the boxes production. This is promoted by the use of road vehicles, which has a significant impact in comparison with maritime transport carried out for exportations. Generally, both packaging solutions yielded comparable environmental outcomes for most indicators. This fact changes when different washing scenarios are proposed. If a complete washing at factory was considered, EPS boxes consistently emerged as the preferred choice. In contrast, relocating the washing station to port facilities might make RPCs more favorable for local and certain regional transport of seafood. Beyond a 160 km distance, both options performed similar. To extend the usability of reusable crates over longer distances, potential actions could include reducing their weight, enhancing their capacity–mass relation, or optimizing electricity consumption during the washing process.

Results obtained provide interesting insights and a framework for outlining potential improvements with the ultimate goal of improving the food sector in Spain. Although environmental performances of both crates yield similar, the choice of reusable packaging options is a response to the growing environmental concerns of stakeholders and consumers. Besides, it is aligned with the strategies proposed in the "Farm to Fork" of the European Green Deal, which supports the use of innovative and sustainable packaging solutions using re-usable and recyclable materials. In this line, the introduction of recycled polymers could extend the lifetime of the boxes while reducing their climate interactions: the higher recyclable ratio of plastics used in the container solutions, the lower environmental impacts in terms of water use, climate change or fossil resources use. However, caution must be taken since there are regulations in force regarding the requirements for the use of recycled polymer, such as that the virgin plastic must come from food use and must comply with exhaustive quality and safety controls to guarantee the correct preservation and non-contamination of the food.

On the other hand, it is important to note that these results are based on the assumptions and limitations previously mentioned and may be subject to change if these are revised. A notable weakness of this study is the need for refinement in the modelling of the end-of-life stage. Future research should incorporate parameters for quality and mass loss in recycling processes to provide a more accurate assessment of environmental impacts. Addressing these weaknesses will enhance the reliability and applicability of the findings, ensuring a more comprehensive understanding of the lifecycle impacts of reusable packaging systems. In this line, forthcoming research endeavors in the field should prioritize the optimization of shelf life, enhancing the number of cycles, and developing collection and washing systems that effectively mitigate the supplementary environmental impact associated with large-scale transport. Furthermore, the exploration of new materials, such as bioplastics, should be thoroughly explored in this area. Moreover, it is crucial to consider the economic and social dimensions of the systems to fully embrace sustainability across its three pillars.

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Table 4
Summary of sensitivity analysis and optimal options in each scenario.

		Impact category indicators					
		CC	**WU**	**RUF**	**AC**	**EUF**	**EUM**
0% washing at factory (100% washing at port)	Local	HDPE	Similar	HDPE	HDPE	HDPE	EPS
	Regional	Similar	Similar	Similar	Similar	EPS	EPS
	National	EPS	EPS	EPS	EPS	EPS	EPS
Baseline scenario (20% washing at factory)	Local	Similar	Similar	Similar	Similar	Similar	EPS
	Regional	Similar	Similar	Similar	HDPE	EPS	EPS
	National	EPS	EPS	EPS	EPS	EPS	EPS
100% washing at factory	Local	Similar	Similar	Similar	HDPE	EPS	EPS
	Regional	EPS	EPS	EPS	EPS	EPS	EPS
	National	EPS	EPS	EPS	EPS	EPS	EPS

Best option: single-use EPS boxes (>10%)	EPS (dark blue)
Best option: reusable HDPE crates (>10%)	HDPE (teal)
Similar options (<>10%)	Similar (light blue)

Atlantic Area.

CRediT authorship contribution statement

Sandra Ceballos-Santos: Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David Baptista de Sousa:** Writing – review & editing, Validation, Investigation, Data curation. **Pablo González García:** Validation, Investigation, Data curation. **Jara Laso:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **María Margallo:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Rubén Aldaco:** Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175452.

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