

Article

Achieving Sustainability of the Seafood Sector in the European Atlantic Area by Addressing Eco-Social Challenges: The NEPTUNUS Project

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Abstract: Fisheries and aquaculture are becoming a focus of societal concern driven by globalization and increasing environmental degradation, mainly caused by climate change and marine litter. In response to this problem, the European Atlantic Area NEPTUNUS project aims to support and inform about the sustainability of the seafood sector, boosting the transition towards a circular economy through defining eco-innovation approaches and a steady methodology for eco-labelling products. This timely trans-regional European project proposes key corrective actions for positively influencing resource efficiency by addressing a life cycle thinking and involving all stakeholders in decision-making processes, harnessing the water-energy-seafood nexus. This paper presents inter-related objectives, methodologies and cues to action that will potentially meet these challenges that are aligned with many of the United Nations Sustainable Development Goals and European policy frameworks (e.g., Farm to Fork, European Green Deal).

Keywords: climate change; eco-label; life cycle assessment; seafood; sustainability

1. Introduction

Nowadays, the seafood sector is facing important challenges that encompass the three pillars of sustainability: namely, environmental issues—stock depletion, adaptation to climate change and marine debris [1]; economic aspects—obtention of enough benefits that make the sector viable over time [2]; and social perspectives—protection of social rights and worker's employment. The Atlantic Area (AA) countries seek to move towards a balance of these three aspects, creating trade alliances and adopting common and responsible seafood production and consumption patterns that provide the product with the necessary quality, safety, and transparency [3]. Its important production of seafood resources makes it one of the main exporters at the European level, reaching production levels of 2.6 million tonnes in 2018 [4]. Most of the seafood originated from capture fisheries at 1.9 million tonnes (Table 1). Small pelagic species were the most heavily exploited by fisheries in the five AA countries involved in the project (France, Ireland, Portugal, Spain and the United Kingdom). From an aquaculture perspective, the most productive country was Spain with 311,087 tonnes, followed by the United Kingdom and France.

Table 1. An overview of seafood production in the Interreg Atlantic Area programme countries from Atlantic fisheries and aquaculture waters in 2018. Breakdown by country and the species by tonnage are also presented [4].

Country	Total (t)	Top Species	Tonnage of Top Species (t)	% of Total Production by Top Species
Fisheries Production				
France	332,666.	Great Atlantic scallop	67,053	20%
Ireland	212,282	Mackerel	57,371	27%
Portugal	128,302	Mackerel	31,946	25%
Spain	843,159	Skipjack tuna	191,795	23%
United Kingdom	440,366	Mackerel	94,907	22%
Total Fisheries	1,956,775	-	443,073	23%
Aquaculture				
France	188,327	Oyster	92,946	49%
Ireland	34,605	Blue mussel	13,889	40%
Portugal	13,512	Clam	4190	31%
Spain	318,597	Mussel <i>Mytilus</i> spp	242,725	76%
United Kingdom	185,296	Atlantic salmon	156,025	84%
Total aquaculture	740,336	-	509,775	69%
Atlantic Area Seafood Production				
Total seafood	2,697,111	-	952,848	35%

From a socio-economic perspective, the seafood sector contributes significantly to the European Union and the global economy, employing 4 million workers in 2017 and generating €180 billion of gross value added (GVA) [5]. Given the weight of this sector, the need to outline tangible actions and design policies focused on reducing or slowing down climate change, achieving energy efficiency or ensuring food security arises. In response, some international institutions have been developing strategies to support sustainability, addressing different solutions. The SDG (Sustainable Development Goal) 12, proposed by the United Nations in the 2030 Agenda for Sustainable Development, highlights the importance of responsible and sustainable production and consumption patterns, betting on a decrease in the generation of food waste [6]. Focusing on fisheries and related activities, the Food and Agriculture Organization (FAO) is especially concerned about the global seafood sector situation [7] and its environmental impacts in terms of overfishing and greenhouse gas (GHG) emissions [8]. According to the FAO, 34.2% of fisheries are overfished; that is to say, their population is below a target level that maximizes harvest [9].

The Common Fisheries Policy (CFP) [10] addressed this issue and set a series of rules for sustainably managing European fishing stocks. Likewise, the EU is actively participating in the circular economy (CE) framework [11], implementing specific fishery regulations [12] and providing information about the environmental performance of products and organisations [13]. As a result, the first CE action plan was completed in 2019, constituting a key part of the European Green Deal [14], which aims to improve people's well-being and achieve a climate-neutral Europe. This new plan presents initiatives along the entire life cycle of products fostering eco-design, sustainable production and consumption, reduction of single-use plastic products, waste prevention and eco-labelling. Regarding the latter, the PEF (Product Environmental Footprint) and OEF (Organisation Environmental Footprint) stand out as methods implemented by the European Commission to quantify and disclose environmental impacts [13]. The first step to obtaining the PEF in the seafood sector has already been taken, consisting of the draft marine fish PEFCRs (Product Environmental Footprint Category Rules) and PEF-RP (Representative Product) study.

There is an increasing awareness of climate change and its consequences on food production and supply chains, which traverses new policies, strategies, projects, and studies [15,16]. Despite the large number of articles related to this topic, vast knowledge resides in technical data, while the theoretical underpinnings in terms of challenges, weaknesses, and strengths of synergies remain largely unexplored. The essential role of innovation, infrastructure, and skill linkages as a means of fostering regional development and matching needs from the point of view of policymakers, industry and consumers must be emphasised. This is further complicated by the need to digitally transform food production and the supply chain, including a necessity to develop real-time solutions to be accelerated through open access and knowledge transfer for the common good [15–19].

As a consequence, it is mandatory to establish unified methodologies and strategies in order to address these challenges. For this purpose, the INTERREG Atlantic Area [20] is a funding programme that promotes transnational cooperation among 36 regions of 5 European countries, contributing to the achievement of economic, social, and territorial cohesion, and implementing solutions to regional challenges in the fields of innovation, resource efficiency and the environment, supporting development and sustainable growth. Under this umbrella, the NEPTUNUS project (EAPA_576/2018) [21] was born, furnishing opportunities for a transition to the CE of the seafood sector in the AA.

The project is based on three main pillars: (i) the development of new methodologies and actions for a CE on a larger transnational scale that has not been pursued previously, taking into account the nature of the seafood supply chains; (ii) the introduction of the NEXUS variable in the decision-making process as a scientific and methodological innovation; and (iii) the definition of a robust framework through the application of a cohesive clustering model that unites stakeholders and addresses gaps and barriers in terms of managing important interacting forces regionally and transnationally. In addition, to ensure the dissemination and capitalisation of the results obtained, the NEPTUNUS project seeks to aggregate from a holistic approach the complementarity of the research groups with expertise in fisheries and aquaculture together with sustainable production and consumption strategies, specifically those related to the circular food economy; methodologies supporting life cycle-thinking applications on climate change and its prevention; green economics; life cycle assessment; water and carbon footprint; and industrial ecology and material flow analysis, especially that which is focused on waste material and secondary resources.

This work seeks to review the scope and methodology of the NEPTUNUS project to deal with the current situation of the fishing and aquaculture sectors. For this purpose, the three fundamental pillars of sustainability will be addressed: environmental degradation, for instance, marine debris [22] or climate change [23]; social perspectives, e.g., people's concern about the environment [24] or worker's rights defence [25]; and economic aspects, for example, globalisation [26] or product quality [27]. Furthermore, the approaches and methodologies applied to the seafood sector will serve as potential guidelines for other food systems interested in alignment with SDGs and European commitments.

2. Research Methodology

Knowledge transfer and clustering of best evidence/data need specific and coordinated strategies to deliver actionable and useful results in terms of sustainability. For this purpose, a ‘nexus thinking’ approach is implemented to the seafood sector with a focus on supporting and enabling the complicated transition towards a circular economy (take-make-use-reuse-remake-recycle) from a linear model (take-make-use-waste). On the one hand, the methodology involves integrating environmental, nutritional, and economic variables that meet regional needs through transnational strategies and, on the other hand, synergies in knowledge and experiences at the local level to help overcome challenges at a global level. In this sense, the NEPTUNUS project is designed in interconnected work packages (WP) (Figure 1) focused on five research lines: (i) the creation of a robust and flexible database composed of seafood life cycle inventories (LCIs) and its subsequent modelling, (ii) the calculation of four footprints (carbon, water, energy and nutritional) and development of a NEXUS ecolabel, (iii) the assessment of the seafood technical cycle (packaging), (iv) the assessment of the seafood biological cycle (waste stream valorisation) and (v) the analysis of different threats and challenges affecting the seafood ecosystem. The following subsections address the different actions developed in the NEPTUNUS project to face the different challenges in the seafood sector to achieve sustainability in the European AA.

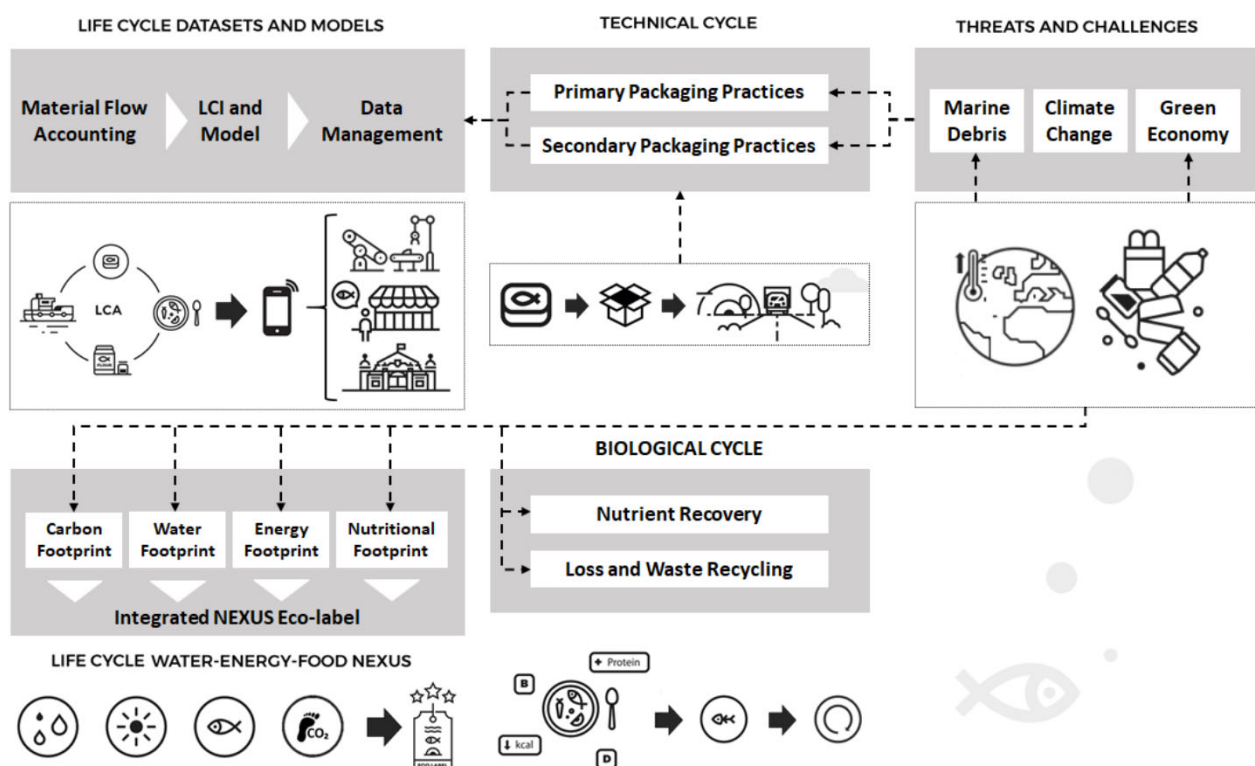


Figure 1. Research lines addressed in NEPTUNUS project.

2.1. Building a Robust Life Cycle Database and Model

Building a robust and high-quality life cycle database is a time-consuming, expensive, and complex task that involves not only expertise in LCA, but also expertise in programming languages and ICT technologies. Hence, the life cycle database developed in the framework of NEPTUNUS provides reference LCI data, as well as environmental impacts of seafood products, focusing on the AA. The database was built mainly on existing LCI databases such as Ecoinvent [28], Agribalyse [29] or World Food LCA Database (WFLDB) [30], thereby giving priority to transparency and traceability. In this sense and in order to assure the comparability and reliability of results, the methodology is aligned to

the main LCA guidelines ISO 14,040 [31] and PEF [32]. Figure 2 depicts the NEPTUNUS database architecture, which is connected to a commercial database for background systems.

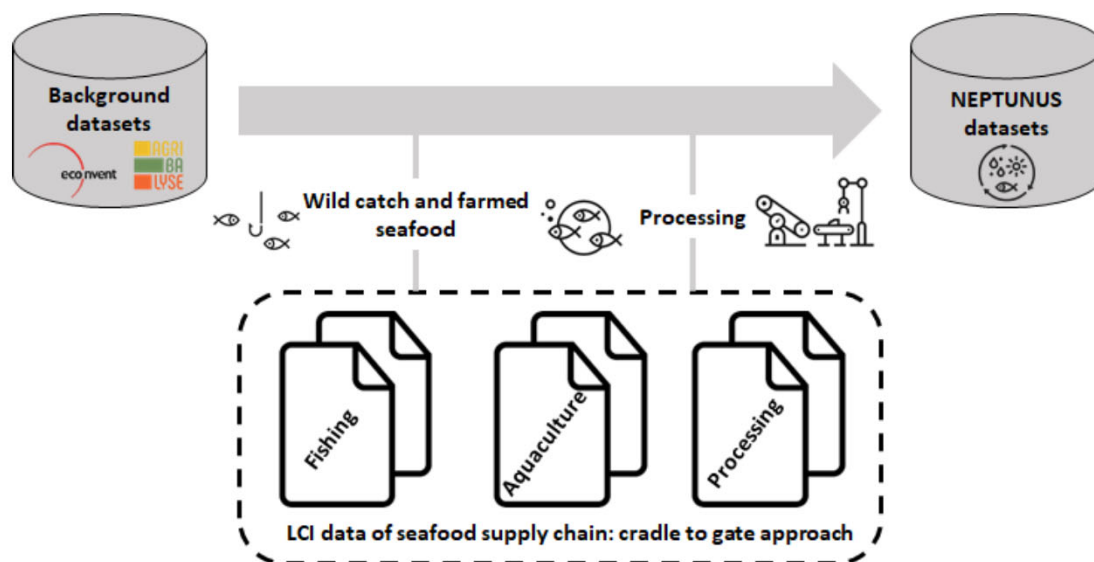


Figure 2. Schematic representation of the NEPTUNUS database architecture.

The database was built with unit processes (i.e., LCI disaggregated data) in a modular way. Due to its modular feature, since it contains the related unit processes throughout the value chain, the datasets can be selected and combined to model seafood processed products: e.g., multi-ingredient processing products, commercial recipes, etc. The latter is especially suitable for experienced LCA practitioners. Therefore, it covers a cradle-to-gate approach, including: (i) fishing operations; (ii) aquaculture activities; (iii) processing; and (iv) production of main packaging materials and ingredients.

The seafood products addressed have been modelled per mass of product. In this sense, the functional unit (FU) was established to be 1 kg of fish landed at port or delivered at the aquaculture gate or 1 kg of prepared seafood for raw fish or processed/semi-processed products. The FU selection and the unit process format simplify the tracking throughout the supply chain, from raw material production, fishing, aquaculture, processing, and transportation of material inputs (i.e., inbound transportation), enabling dataset modelling by users. Similarly, waste treatment and food losses were also accounted for and tracked in the datasets.

When dealing with multi-functionality, the allocation method used in the database is mostly based on mass allocation. In this sense, in accordance with the PEF method [32] and ISO 14,044 [33], the following pattern was followed in the decision hierarchy: (i) subdivision or system expansion; (ii) allocation based on physical properties; and (iii) allocation based on non-physical properties. Table 2 depicts the modelling instructions and the allocation rules followed per activity in the database. In addition to this, the allocation approach followed per activity was also defined in each dataset. In case of doubt, the user can check allocation procedure descriptions in each dataset's corresponding documentation.

Each LCI dataset includes a critical review report which assures transparency and reliability. The report provides valuable information related to the geographic, time, and technological representativeness of the inventory data. The datasets were built on the requirements of the International Reference Life Cycle Data System (ILCD) Data Network [34]. Specifically, datasets were formatted following the "ILCD Data Network—Entry-level". In addition, the goal and scope of the database are aligned with PEF methodology [32], and, therefore, the critical review reports follow a similar structure, providing information in terms of: (i) goal and scope, which includes detailed information regarding the FU selected,

system boundaries, assumptions made and limitations; (ii) life cycle inventory analysis with a detailed description of the modelling choices and other issues such as the allocation approach conducted, air/water emissions estimation (e.g., stationary fuel combustion derived emissions or mobile fuel combustion derived emissions), electricity mix, primary and secondary (background datasets) data used, list or detailed bill of materials or ingredients, end of life, and cut-offs; (iii) Circular Footprint Formula (CFF) parameters used, detailing where the CFF has been applied; and iv) life cycle method implemented, reporting life cycle impact results.

Table 2. Allocation rules per activity data.

Activity/Datasets	Allocation Rule	Modelling Instructions
Fishing	Mass	Despite fishing gears selectivity, several species are caught apart from target species. In this sense, allocation shall be done on the basis of the total amount of catches of each species.
Aquaculture	Mass	Aquaculture operations are usually focused on the production of a single species, although in some cases, it is possible that several species are produced together. In those cases, the same procedure as in fishing allocation shall be applied.
Seafood processing	Mass	This is an example of a multi-product industry, so that different products can be obtained from a single species of fish. For example, from hake, fillets, tails, fish sticks and croquettes could be obtained. In this case, the total annual production of each production line shall be used to establish the allocation factors. It is important to note that the edible weight should be used to establish the annual production.

The critical reports were reviewed and validated by qualified external reviewers with LCA expertise in the field of seafood products, guaranteeing data quality and reliability [35]. Finally, it should be noted that datasets are intended to be accessible and usable to all users. Thus, the data formats meet the requirements for interoperability in terms of flow nomenclature and metadata descriptors defined by “The Global LCA Data Access” network (GLAD) [36].

2.2. Creating a Nexus Ecolabel

As mentioned in the introduction section, actions have already been initiated in the fisheries and aquaculture management framework that aim to address changes and recognize threats to climate change [37]. Among these, one that encompasses all stakeholders is ecolabels, as they open the way to implement legislative measures (policymakers), are applicable to products (companies) and provide useful information to customers. Moreover, ecolabels can be a useful tool to promote sustainability and raise awareness on marine conservation and more collaborative business models among producers [38].

The most globally-recognized ecolabel for fishing activities is the Marine Stewardship Council (MSC). It was proposed in 1997 and focuses on the impact of the fishing activities on the marine ecosystem and overexploitation of its resources through the commitment of compliance of the following principles: (i) the state of the exploited stock, (ii) the impact on the ecosystem structure and function and (iii) an effective management system [39].

At the European level, a label for organic food (KRAV) is implemented in Sweden, which considers several environmental aspects covering multiple stages of the life cycle for seafood products (minimizing bycatch, avoiding damage to the seabed by limiting fishing gear such as trawling, animal welfare and recyclable packaging). Another example of an ecolabel is Pescaenverde, which is the first type III ecolabel (i.e., sustainable declaration of a product or service on a voluntary basis) considering a life cycle perspective in the fisheries sector in Spain. It has been based on the evaluation of the environmental impacts related to seafood products from the Carbon Footprint and the Edible Protein Energy Return On Investment (ep-EROI) ratio. In this way, this certificate provides valuable information on fuel efficiency and energy intensity linked to vessel operations [40].

On the business-to-consumer (B2C) level, companies are more concerned about showing their customers the environmental profile of the products they commercialize, as the demand for green or environmentally friendly products has been growing steadily in recent decades. Ecolabels are a simple and direct way to meet this target. Thus, ecolabelling presents a potentially useful starting point towards sustainability; thus, enlarging the niche market of consumers increasingly demanding low-impact seafood products while establishing a group of producers increasingly interested in minimizing impacts from their products [41]. This also potentially unlocks a pathway towards informing behavioural change by influencing and positively disrupting attitudes and perceptions in order to overcome consumer barriers [19,42]. On the other hand, those on the business-to-business (B2B) level are facing increasing pressure to work with products containing ecolabels in order to meet procurement requirements [43]. In addition, suppliers are increasing partnerships with eco-friendly manufacturers who work in accordance with the ISO standards [44].

Additional aspects to be met by the application of eco-labelling to AA include the environmental profile associated with fishing or aquaculture encompassing the processing activity (where applicable), as well as the positive contribution of seafood intake. Therefore, a simplified transition of the seafood sector towards a CE approach should prioritize the harmonization of different methodologies for calculating environmental footprints together with the contribution of the food subsystem into a single score. This would provide clear, accurate and simplified information on environmental and nutritional aspects for consumers. Currently, most seafood labels provide limited information for consumer decisions and are not based on environmental information. Although the economic factor is often the most influential factor in the choice of the consumers, some previous surveys reported that consumers are willing to pay 15–30% more if the ecolabel guarantees that the seafood is healthy and sustainably produced [45]. However, label overload and gaps in understanding could lead to confusion [46].

To undertake this objective, LCIs collected from different seafood systems along the AA were assessed under a water-energy-food nexus perspective, encompassing the inseparable synergies between resource extraction (food) with water and energy consumption. This approach can help to analyse a complex system consisting of several subsystems with multiple interconnections [47]. To proceed with this joint analysis in the face of the challenges of sustainable seafood production, it is the life cycle assessment (LCA) methodology that is considered a reference as it addresses a global, quantitative and objective approach to the impacts associated with a process, product or service [48].

Among the most commonly used indicators in environmental impact assessments, there are three of notable importance, carbon footprint (CF), water footprint (WF) and energy footprint (EF), that are especially relevant for this analysis, as they report the main environmental issues associated with the fishery and aquaculture sectors:

- Carbon footprint: quantifies greenhouse gas (GHG) emissions, the main driver of climate change, and helps understand how to mitigate it. LCA studies have shown that the consumption of marine fuel and its subsequent burning by fleets are the main environmental burden from fishing production [49], together with feed production from farming seafood products [50];

- Water footprint: fishing is a high-water-demander and wastewater producer. This is particularly noteworthy in the processing stage during the cleaning and de-scale steps [51];
- Energy footprint: the consequences of rising fuel prices, taxes levied on emissions and tightening environmental regulations lead to the implementation of energy efficiency plans [52].

On the other hand, the nutritional footprint (NF) of the evaluated seafood species could be measured through the nutrition-rich food (NRF) index, as it allows the healthiest foods to be identified based on their nutritional value [53]. Moreover, this should include specific nutrients that are fundamental pillars in the human diet and are often present in this type of product, such as iodine, selenium or omega-3 fatty acids [54–56].

Despite all the benefits that ecolabels can bring to promote sustainable seafood, one of their main drawbacks is that they focus exclusively on the most knowledgeable or environmentally involved consumers, reporting low market shares [57]. To cope with this common shortcoming, more conventional market strategies need to be applied. This might include, for instance, establishing a dynamic target audience to broaden the potential consumer profile to reach people who are less aware of a product's sustainability or who are less motivated to purchase this type of good if it involves an additional cost [58].

Therefore, to create a successful path for the creation of an eco-label and its adoption by the market, it is vital to consider a two-step procedure: to catch the attention of the consumers more inclined to purchase environmentally certified products, and once this has been achieved, to engage the public who prefers to choose those alternatives that are already commercially available.

2.3. Packaging Eco-Design and Waste Management

Packaging is an unquestionably essential aspect of FSC due to the insurmountable distance between production plants and consumption. The high dependence of markets on imported products [59] and globalization has made the role of packaging crucial in protecting products and preserving their quality in transport and distribution operations. However, numerous factors must be taken into account when choosing the appropriate packaging, both from an economic and technical point of view, but also from an environmental perspective.

Later stages of the food supply chain, including retail, packaging and transport, usually do not have a significant contribution to GHG emissions from food [60]. Particularly, packaging has up to 15% of the total carbon footprint in chilled, frozen, and cooked seafood products [61–63]. In contrast, cans of tinned seafood suppose an important contribution to the climate change potential of the product [49,64–66]. On average, packaging of canned seafood made of tinplate, aluminium or glass contributes 42% of the product's climate change impact and 27% of the product's weight, indicating that for such products, packaging production is commonly a major bottleneck [67]. This demonstrates that the type of packaging material could have a significant influence on the product's environmental performance. Unlike certain materials, plastic has a low contribution to seafood products' climate change impact, mainly due to its lower energy requirements in the production phase compared to other materials (e.g., aluminium) [67]. As an example, plastic packaging can be the most environmentally friendly option for the distribution of fruit and vegetables compared to reusable plastic crates with single-use cardboard boxes [68]. However, plastic can only be recycled a limited number of times, and its use to substitute virgin plastic could be restricted to non-food packaging applications if food and non-food plastic waste are mixed [69]. In addition, around 52% of plastic pollution is carried by rivers, and plastic leakage into the ocean from land-based sources has emerged as an important cause of different marine ecosystems damages [70]. These impacts are still not considered in LCA studies, and therefore, the subsequent fate of polymers and their products in the marine environment might be underestimated [71]. Viable alternatives to plastic from bio-based materials have emerged [72], but they still face challenges in their disposal effectiveness

and impose changes in plastic separation systems. Bio-based materials should be sent to biowaste disposals instead of recycling streams, as happens to other types of plastics [73].

At present, less than 30% of the plastic collected goes to recycling, and a significant share of this amount leaves the EU to be treated in third-world countries, where different environmental standards may apply. The material recyclability rate or the available infrastructure are key factors of recycling processes. For example, in the case of plastic, polyethylene (PE) and polypropylene (PP) account for around 50% of Europe's plastic production, and polyethylene terephthalate (PET) accounts for 8%, but unlike PE and PP, PET's chemical properties allow it to be recycled in a way that maintains its quality [63]. Increasing our ability, capacity and motivation to recycle is fundamental to building a CE that transforms and adds value to waste [74]. Significant environmental improvements can be achieved with simple changes in the EU waste management systems. For instance, there is space in the EU to increase light packaging collection rates and to collect more from bulk containers using mechanical-biological treatment plants where some plastic could be recycled instead of being sent to landfills or incineration [75]. Furthermore, the percentage of plastic waste that is effectively recycled can be improved by the imposition of constant demand and avoiding export of waste, creating a design for recycling (e.g., a monopolymer design), and promoting the collection and advanced end-of-life technology. Besides, these environmental burdens will continue to increase whether the production and disposal of packaging, regardless of the portion that is recycled, is not curbed. In this sense, to support a transition towards a CE, a single-use plastics directive [11] from the European Commission was officially adopted in 2019 and included a ban on the disposable of single-use plastics and measures to make all plastic packaging in the EU recyclable by 2030.

On the other hand, it is imperative to consider secondary aspects, such as food waste, transport, or product preparation, among others, in order to comprehend the packaging role as a whole [76]. Other indirect environmental burdens related to packaging, for instance, those associated with resources or energy waste during production, are also usually underestimated, even though they may present an opportunity to improve the overall environmental performance of the good [67]. Seafood loses its quality significantly faster than other foods, so it is important to ensure that the least amount is wasted along the FSC. Estimates on seafood loss showed that 40–47% of the edible U.S. seafood supply was lost or wasted during the 2009–2013 period, and the greatest portions of this occurred at the consumer level [77]. As shown in Wikström et al. (2019) [78], for meat, fish and eggs altogether, the climate impact from food wasted could be larger than the climate impact from packaging, and trade-offs need to be verified through different types of packaging design approaches. At this point, packaging innovation could be crucial in stopping food waste, particularly seafood products [79].

By infusing eco-friendly strategies into the design, retailers are able to promote innovative products that may lead to significant economic and environmental savings. The packaging of a product is often the best way to visually engage and attract potential consumers. Therefore, eco-design applied to packaging could add extra value to Atlantic seafood products. Eco-design actions applied to primary packaging are usually related to the adaptation of current packaging by: (i) using as few raw materials as possible; (ii) selecting materials that are sourced sustainably (e.g., can be regenerated in a reasonable time-frame); and (iii) facilitating disassembly and recycling, thus saving resources that are replaced by recycled materials [74]. However, a holistic approach to packaging along the seafood supply chain clearly needs to emerge with package eco-design. Accurate recovery rates of recycling materials, different waste management strategies like reutilisation, and more packaging disposal options (for instance, anaerobic digestion), together with trade-offs between seafood loss and waste and environmental footprint of packaging, should be considered in seafood eco-design strategies [67].

Another important strategy is to involve consumers to foster recycling behaviours and ensure effective acceptance of the use of more appropriate packaging solutions. Under

NEPTUNUS, a survey was designed to assess the knowledge and barriers of consumers on seafood packaging waste management in different AA countries. Portugal has the highest consumption of seafood in Europe, 61 kg per capita in 2018, followed by Spain with 46 kg, while Ireland with 23 kg is below the European average (24 kg per capita) [80]. Furthermore, the way in which fish is prepared and consumed (e.g., fresh, frozen, preserved) varies widely between European countries. Given the great differences in habits and in the type of seafood products purchased, the results of this study can help to understand consumption patterns, as well as the level of knowledge and environmental awareness of consumers about the end of the life of packaging. It is expected that the results will support the development of public policies and help companies to promote the efficient use of seafood packaging based on a CE (Figure 3).

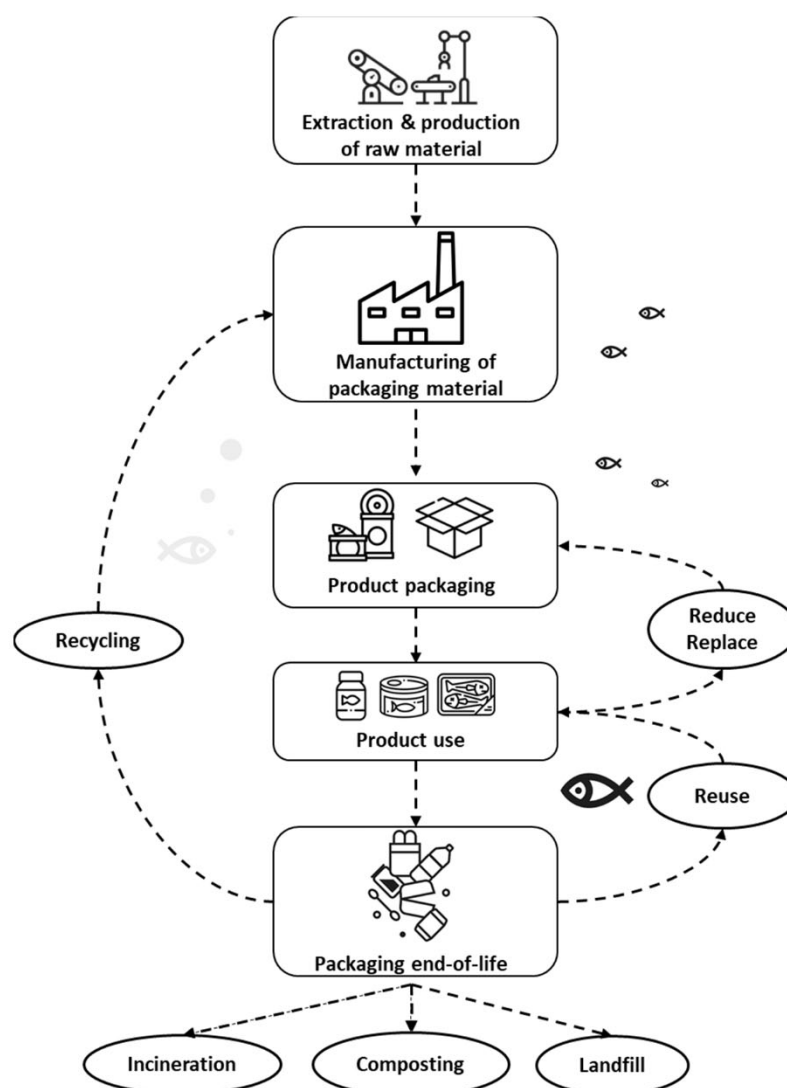


Figure 3. Circular economy principles applied to seafood packaging.

2.4. Giving a Second Life to Seafood Waste

Waste arises from the grading, processing, packaging, distribution, and consumption of seafood products [77,81,82]. This waste can include the loss of nutrients and compounds in wastewaters, discarded raw material, supply chain leakage or mismanagement [83–85]. An example of this is the high degree of food loss and waste (FLW) that can happen in (fresh) fish and seafood supply chains, which has been estimated to be 36% in the AA region [82]. This degree of FLW is unsustainable given the (often competing) need for

protein sources to feed a growing population and the need to reduce the environmental burden of food activities [86–88].

More responsible management and valuation of the nutrients and products that can be derived from seafood waste streams is required. Furthermore, the distance between consumers and their food has increased by an incredible margin in the last 50 years. This dissociation with the food production process and the food supply chain has compounded the levels of FLW seen today [85,89,90]. One of the ways in which these levels of FLW are being combatted is through the use of European policies [11,91], which support a transition to a CE.

A CE approach is something that must be managed from a holistic point of view, i.e., from natural resource consumption, to processing and to waste management; in essence, it must be managed from a life cycle perspective. The first step to achieve a CE is favouring the reutilization of what would initially be considered waste. An opportunity for improvement by taking advantage of the potential of the nutrients contained in FLW can only be achieved by minimizing the amount of waste generated and by considering waste that is unavoidable as a new resource. In this line, it is imperative to link high-value residue streams with LCA and valorisation opportunities. Typically, there are five avenues for the valorisation or reuse of seafood waste streams. These range from low-value opportunities such as energy and fertiliser, median-valued options such as feed and food and high-value opportunities (Figure 4) such as biotechnology and nutraceuticals [92–95]. In all the valorisation opportunities outlined above, there is a need for full nutritional characterisation of the waste streams. This characterisation can help to demonstrate the higher output values associated with food, feed and nutraceuticals when compared with waste-to-energy strategies. Recently, there has been a trend to develop datasets on these waste streams to facilitate this appropriate and strategic utilisation [96,97]. These datasets will play an important role in increasing awareness of the valorisation potential within these waste streams and help to inform consumers, processors, regulators, and other supply chain actors of the value that lies in seafood waste [96].

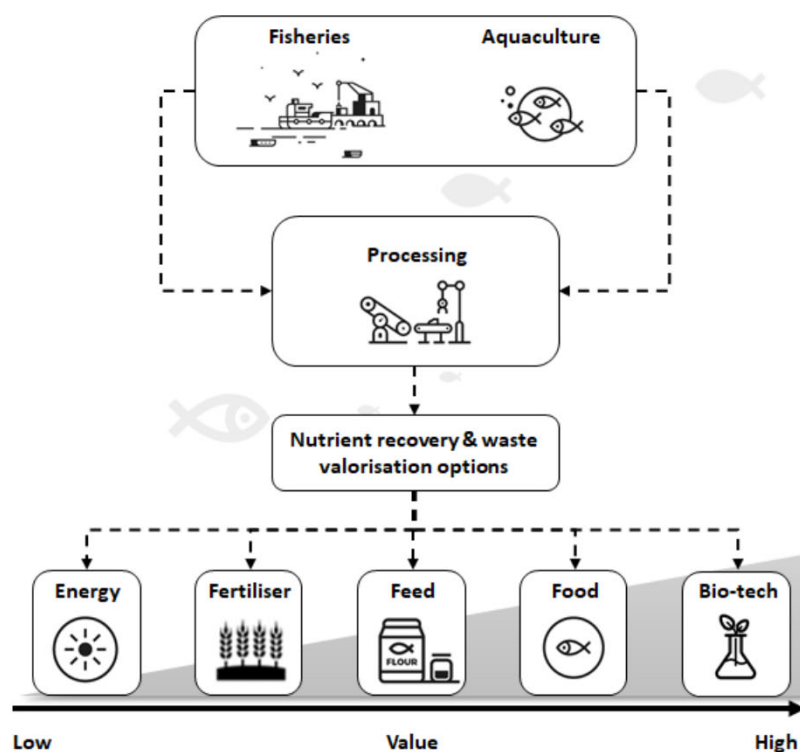


Figure 4. The nutrient recovery and waste valorisation options for seafood waste streams. Low- to high-valorisation processes are indicated by the x-axis.

It is crucial that these valorisation and benchmarking activities be underpinned and supported by an LCA framework when being considered as part of a transition to a CE [98–100]. In the NEPTUNUS project framework, a water-energy-food nexus approach is applied to valorisation strategies that obtain nutrient-rich products to replace other polluting ones (such as synthetic fertilizers), thus increasing the economic benefit while avoiding environmental damage by decreasing NO_x and CO₂ emissions. As an example, anaerobic digestion presents huge advantages in supplying by-products like biogas fertiliser, achieving higher nitrogen availability than undigested sludges [101,102]. With the utilisation of this technology, as well as others, NEPTUNUS can complement the European reference document on Best Available Techniques with recommendations based on a CE applied to the food sector and prevention and reutilisation options. Aligning the research programme of NEPTUNUS with the current EU level actions against FLW and the United Nations Sustainable Development Goals, particularly goals 2 (zero hunger), 11 (sustainable cities and communities) and 12 (responsible consumption and production) [103,104], will help to identify opportunities and strategies that complement policy and operator considerations.

The Union's energy policy recognises the increasingly pressing challenges in our society and aims to develop strategies linked to achieving a single energy market with lower energy costs, promoting competitiveness and energy security, and boosting sustainable and efficient energy use [105], which raises the possibility of waste-to-energy options. Seafood waste management is often neglected in order to save resources [92,95]; however, its reutilisation, recycling or valorisation could produce valuable by-products, such as food or feed [106], or be used as a resource for biorefineries in an efficient and profitable way [107]. In the NEPTUNUS project, three strategies are proposed: non-biological volume or weight reduction, thermal processing, and biological digestion. The latter can help recover and mitigate the loss of nutrients and valuable compounds from seafood value chains [100]. In addition, biological treatments can operate with lower cost and environmental impact [94], making them an ideal means of treatment and valorisation from a CE and an operator perspective.

3. Identifying Threats and Challenges of Fishing in the Atlantic Area

The transition towards a circular economy, the adaptation to climate change and the harmful consequences of marine litter are only some of the chief challenges of the fishing sector in the AA. The need to act on the entire seafood supply chain is evident, as environmental impacts occur both at the harvesting [108] and production stage [8,109], but also influence policy decisions. Therefore, the AA presents an appropriate framework to propose regional strategies regarding the mitigation and adaptation of climate change, generating global repercussions.

In addition, the eradication of marine litter is crucial to ensure the wellbeing of current and future generations. Marine debris is a hotspot of the seafood sector that should not be underestimated since it could lead to human health problems [110], damage to ecosystems, or negative socioeconomic consequences caused by challenges like ghost fishing, fostering by derelict fishing gear [111], interference with food webs and food-borne toxins. As a consequence, it is mandatory to adopt actions or strategies in the AA to be able to deal with these troubles.

3.1. Marine Debris

Large quantities of plastics leak to the ocean as marine debris (with estimations of 4.8 to 12.7 million tons in 2010) and generate adverse effects on the environment [112]. The seafood sector, including fisheries and aquaculture, is particularly concerned by this challenge because (i) an important proportion of marine debris are generated by fishing activities such as abandoned, lost and discarded fishing gear [113] and (ii) marine debris have strong socio-economic and environmental consequences with direct repercussions on fishing, including contamination with microplastics, reduction of income and lost fishing time, and retraction of catches associated with debris in nets [114].

To ensure its sustainability, fishing activities must reduce the use of plastic and control the losses produced in the whole supply chain, for which mapping plastic flows along the life cycle of the product is key. However, the current LCA database does not consider loss and impacts related to plastics debris in the environment [26]. Recent research is under development in order to tackle this challenge.

Concerning life cycle inventory, Loubet et al. (2022) [71] proposed the first methodological framework to measure the plastic flows of the life cycle of seafood products based on the suggestions of the Plastic Leak Project [115], consisting of quantifying the loss rate and the final release rate. In this methodology, applied to French seafood products, loss rates are defined for 5 types of micro- and macro-plastic losses occurring at different life cycle stages of seafood products: (1) abandoned, lost, and discarded fishing gear (ALDFG) and (2) marine coatings (during fishing activities), (3) polymer pellets (during the production of plastic), (4) tire abrasion (occurred in transportation), and (5) plastic bungle (during end-of-life). The main outcomes reveal a plastic loss between 74 mg and 4350 mg of plastic per kg of consumed fish. An average of 100 mg of plastic/kg of fish at the consumer is lost for most species, including mackerel, albacore and herring caught with pelagic trawl; saithe caught with bottom trawl; and yellowfin and skipjack tuna, anchovy, and sardine caught with purse seine. In the counterpart, the major plastic losses are produced in the capture of fish that need high weights of passive fishing gear, in which the fishing gear (e.g., longlining or trammel net) and tire abrasion are the main hotspots in terms of average loss rates. Nevertheless, these loss rates are quite variable, showing the main plastic loss to the environment in the poor management of the final packaging.

Leaving aside the environmental issues, it is also necessary to assess their impacts on the ecosystems and on human health. Recent initiatives have been launched to develop life cycle impact assessment methods, especially in the MariLCA working group [116]. It is expected that over time, plastic loss streams and environmental impacts will become part of LCA outcomes, enabling the development of eco-design strategies, as well as providing other benefits.

Despite the advances in the LCA framework, there is still the priority of the adoption of preventive and corrective measures to curb plastic losses during the life cycle of seafood products [117]. On the one hand, increasing visibility and identifying ownership of fishing gears, using technologies (radar) to track gear location, changing to biodegradable plastic materials, or controlling passive gears are some actions to prevent this problem. On the other hand, corrective measures embrace, for instance, the encouragement of the retrieval, detection, and removal of ALDFG by means of affordable and accessible port reception installations. In this context, the NEAFC (Northeast Atlantic Fisheries Commission) suggests strategies for purse seine, trawl, and demersal longline, including the marking of anchored and drifting fishing gear to know its position, the identification of marker buoys, etc.

It has also been shown that plastic packaging at the end of life and transport by truck generating tire abrasion are two main sources of plastic losses that must be reduced. Concerning packaging, eco-design strategies (see Section 2.3) can be developed to decrease the quantity of plastics used or to substitute petro-based plastic with bio-based and biodegradable plastics. It is also necessary to improve the end-of-life management of plastics (through recycling) in order to avoid plastic leakage. Microplastic losses from tire abrasion could be reduced through more local circuits for lowering transportation distance with trucks.

3.2. Climate Change

The Intergovernmental Report on Climate Change [118] is referred to as “a code red for humanity” by the United Nations general secretary Antonio Guterres. The report compiled by 200 scientists from 66 countries highlighted the link between human activity and climate change. Climate change is causing the ocean to heat, lose oxygen, expand, and acidify. From a seafood perspective, this is putting increasing pressure on fish stocks with the potential extinction of some species [119]. Severe weather events as a result of climate change affect the level of seafood production, the livelihoods of communities that depend

on fisheries and aquaculture, and the future sustainability of the seafood sector [120,121]. This recognition that climate change threatens the seafood industry and quality of life on a global scale has led to an increasing amount of attention being paid to adaption and mitigation strategies for the sector [122,123].

The European Commission 2030 climate and energy framework has a target to cut GHG emissions within the territory by at least 40% below 1990 levels. This entails recognising the need for effective and sustainable responses in the seafood sector there to respond to the urgent threat of climate change through mitigation and adaptation measures [124], with the European Green Deal aiming to achieve climate neutrality by 2050. The 'farm to fork' strategy in the area of seafood focuses on climate change in the 2022 Common Fisheries Policy review and aims to support the algae industry and offer strategic guidelines on aquaculture to cultivate a sustainable 'green' pillar for the economies in the European Union. Seafood producers face the challenge of meeting regulations, production, and targets for climate change [100].

Seafood is expected to become increasingly important in future food systems and healthy diets, driven mainly by policy and consumer demand [125]. According to Fletcher et al. (2021) [126], in order to respond to these demands and environmental and social challenges, this transition will require the adaptation and mitigation of business practises in the seafood sector to increase resilience. Previous research describes how firms adapt their physical, human and firm resources in response to market changes [127–129]. These dynamic capabilities include the seafood producers' existing entrepreneurial experience, existing knowledge and learning to identify what resources and competencies need to be used for market changes [130,131].

Numerous methods have been used in sustainable fishing practices to reduce the ecological impacts of bycatch, including modifications of the gear used, quotas, banning discards, and time/area closures [132]. Many researchers [126,133,134] have suggested a reframing of the narrative around sustainable seafood to incorporate the complete supply chain and a focus on reusing waste by-products as a valuable resource.

Public perceptions of sustainable seafood and climate change vary and are mainly focused on ecological concerns [133], though the impacts along the supply chain are substantial. While current perceptions of sustainability in seafood are primarily focused on ecological concerns, impacts stemming from the material, water and energy demands of the seafood supply chain can also be of increasing importance to consumers [132]. For example, in order to reduce direct potential impacts from seafood packaging, it was recommended to increase recycling [67].

According to Tseng et al. (2020) [135], collaboration in the sustainable seafood supply chain should incorporate social, economic and environmental aspects. Many researchers have highlighted the importance of the triple helix model to innovative sustainable strategies in the seafood supply chain [136–138]. Researchers agree that collaboration between actors in the supply chain and stakeholders is key to aligning innovation and sustainability and, in turn, meeting UN SDGs [139,140]. The quadruple helix innovation strategy bridges the gap between policy and practice for academia, industry, policymakers and society as it forms collaborations between the actors in the supply chain and the stakeholders to bring to fruition a chain of environmental responsibility for sustainable seafood [128,138]. This framework also supports and enables training and outreach for communities transitioning to low-carbon economies, including sustainable food production [23].

3.3. Green Economy

The CE is considered an improvement opportunity to move towards sustainable and efficient models. A CE is responsible regarding the use of resources and is beneficial from a socio-economic point of view. However, the right tools must be in place to determine the pros and cons, both environmental and economic, of this transition. The characterization of economic costs and benefits in different stages of the value chain, from extraction to final storage, is essential. Unfortunately, as is the case in other sectors [141], the decision-making

process to address the CE in the seafood sector is hampered by the limited number of socio-economic studies [142]. Even though the relationship between the tools of environmental assessment and economic performance analysis is well-established [143–147], studies do not usually include information on the transformation of the economic system beyond resource and waste management [148].

It is essential to provide value-chain stakeholders with indexes that enable them to define their sustainable strategies towards a CE [149], for instance, those based on the economic performance of seafood products. Indeed, the reduction of hidden costs, the improvement of added value or the increase in the employment rate can be highlighted using appropriate economic tools. There are numerous tools that enable these analyses, and the choice depends on different factors, such as the scale, availability of data and metrics. Material flow cost accounting measures the consumption of materials and energy, as well as waste generation, using physical and monetary information and applying the cost absorption method [150]. For its part, life cycle costing appraises the direct costs of the whole life cycle of a product, whereas the objective of the cost-benefit analysis monetises cost benefits and aggregates them into a single scope and unit of measurement [146]. Finally, the input-output model (IOM) assesses the relationship between the input and output flows in an economy. Direct impacts (for a given activity), indirect impacts (for the activities providing direct and indirect goods and services to the given activity) and induced impacts (through employees' consumption) on production, employment, and added value are assessed according to changes in levels of output [151].

As part of the NEPTUNUS project, the use of IOM has been favoured, as it calls upon territorial development and local stakeholders for the uptake of CE practices. Indeed, IOM integrates all upstream intersectoral exchanges through the commercial interactions between different companies and public entities (suppliers/clients/subcontractors exchanges) on a given territory. This territorial approach relies both on geographic proximity that favors material and energy exchange between industries [152] and institutional and organizational proximity based on stakeholders' interactions [153]. At this scale, local issues are better captured, cooperation between stakeholders is facilitated, and economic and communicational proximities can be easily promoted, even if operational complexity may require working at a broader scale [154]. The territorial approach builds on industrial and territorial ecology, an operational approach that draws on natural ecosystems to strive for the optimal management of materials and energy [155]. Both industries and local institutions should benefit from the implementation of industrial and territorial ecology. Indeed, products with a higher added value could be marketed thanks to synergies between waste producers and users and increased competitiveness based on new material production. Local institutions will also benefit from the creation of activities and employment that cannot be relocated, the development of territorial attractiveness and the reinforcement of industries' territorial anchorage and improved resilience.

Applying IOM to a CE sector can provide useful insights on how this sector will affect the upstream value chain and thus give value-chain actors crucial arguments to inform their new transformative strategies.

4. The Importance of a Transnational Approach

The fishery and aquaculture sectors face several environmental issues throughout the seafood supply chain related to fishing, aquaculture production, processing, packaging, and transportation. These issues often affect transnational geographical areas (e.g., marine debris) or represent issues of global interest (e.g., climate change). Therefore, the attempt at individual resolution of each company, region or nation is not sufficient to solve the problems presented. Besides, the need for measurement and communication of the environmental performance of the seafood and aquaculture sectors through tools such as footprints or eco-labels crosses borders, creating the need for the harmonization of approaches and calculation methods. Furthermore, sustainable and multilateral research cooperation through transnational strategies and policies based on a CE is needed to reduce

the use of resources in seafood processes by recycling and valorising the waste outputs into production and consumption systems, minimising the environmental impacts of seafood products, and incorporating competitive products into green markets.

In this context, cooperation in a transnational approach is key to achieve efficient and innovative solutions, adopting a cluster model in which all stakeholders are involved and collaborate in addressing gaps, barriers, and future challenges. This clustering is also relevant for balancing these concerns with economic aspects during policy- and decision-making. Moreover, sharing knowledge and experiences at the regional level can help to address these challenges at the global level. In this sense, the NEPTUNUS project brings together several partners from five countries (Ireland, France, Portugal, Spain, and United Kingdom) (Figure 5), focusing their joint efforts on a strong and cohesive multilateral research cooperation for the development of more sustainable and coordinated strategies for the production and consumption of seafood products that meet regional needs of the seafood sector and also meet needs across jurisdictions in the AA. Moreover, there is a growing awareness that an effective interconnection between knowledge and complementary experience on the development and implementation of environmentally efficient processes and products supports the generation of non-fragmented environmental policies for the seafood and aquaculture sectors.

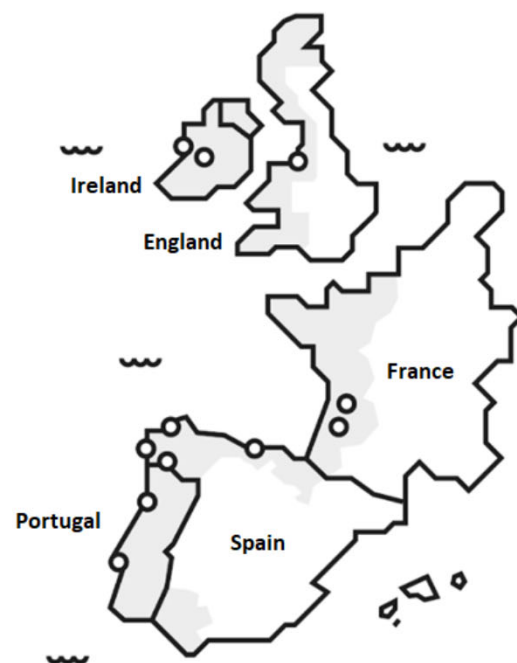


Figure 5. The countries covered by the Interreg AA and the NEPTUNUS project.

5. From Researching to Stakeholders

NEPTUNUS developed a dissemination and communication plan considering the target audiences and selecting the appropriate tools and channels to meet their information needs. An important part of the NEPTUNUS project was to involve the stakeholder (producers and consumers in this case) in the early stages of the process to allow the alignment of the research to industry requirements and expectations. In this way, the project could guarantee its commercial impact. Therefore, the project, across the different WPs, had the active involvement of producers and citizens, as well as other target audiences beyond academia, in order to increase the societal impact of NEPTUNUS achievements. In this sense, all the questionnaires considered to collect the data were done for the partners in face-to-face meetings with the companies, fishermen, etc., to guarantee the quality and replicability of the data throughout the AA. However, in the same line, the project contributes to meeting societal challenges by promoting more transparency from sea to

fork, focusing on the project's impact on environmental aspects. In this way, the seafood packaging survey, the results of which are currently being analysed, will make it possible to connect with the consumers' knowledge about good packaging recycling practices, among other things.

Regarding the dissemination plan, the consortium has tried to open the NEPTUNUS knowledge across open-access scientific and industrial publications in international peer-reviewed journals, showing scientific excellence and paving the way towards more sustainable seafood production and trade. In this sense, the members of the consortium have published several scientific publications in journals with previously identified impact factors (Journal of Industrial Ecology, Science of the Total Environment, Current Opinion in Environmental Science and Health). At this moment, 11 papers have already been published, and there are 3 more under revision (Table 3). Additionally, several conferences (8 in total) have featured NEPTUNUS presentations, such as aquaculture conferences (European Aquaculture Society, Northern European Aquaculture Event), general marine events (II Conference of Young Marine Researchers) as well as specific events such as the one related with environmental product declarations (7th EDP International Stakeholder Conference). In the same line, the consortium participated in events of other AA projects (i.e., Circular Seas) and other European projects (Oceanets, funded by the European Union EASME's European Maritime and Fisheries, EXTRA-SMEs (Interreg new project)) to cluster with related European partners in order to maximize impact in common areas and try to achieve better results through cooperation between organisations of different projects. Besides, dissemination is increasingly taking place early in the research life cycle, and this broader and more interactive engagement is becoming an integral part of the entire research workflow. Consequently, the project is highly involved in dissemination from the first stages of school, based on the principle that students should try to "co-produce" their education in a similar way to the industry. The seminars in schools, as well as other initiatives such as The IX European Researchers' Night (held on the last 24th of September in more than 370 cities across Europe) were platforms to reach the incipient researcher, trying to develop students' competencies through critical analysis or brainstorming methods.

The main objective of the projects' communication measures is to inform and promote the project and its results in a non-technical way to reach a broader audience. Special attention will be paid to the treatment of public policy messages by the transmission of key messages and through the different deliverables of the project, such as the white papers already published or in preparation, that seek to promote the concepts of a CE in the seafood area. NEPTUNUS has created a visual identity across its logo, emphasizing the circular point, and across the project slogan: "Providing opportunities for a transition to the CE of the seafood sector in the Atlantic Area", where the field and location of the process are clarified to facilitate project engagement. A project website was also created, which is very intuitive both in its design and in the way the content is formulated. Moreover, the project created social media accounts (e.g., Twitter, Instagram) for the project and linked them from the project website with the aim of a sustained presence with new and engaging content to reinforce the project's message and to try to establish a core group of followers to disseminate key findings or give important updates on the project. In addition, hard-copy brochures were produced to communicate/connect the more human side of research in face-to-face networking events.

It should be borne in mind that the COVID restrictions have forced the project to make a greater effort in contacting stakeholders, such as producers or consumers, in a more virtual way and have reduced the capacity for dissemination and communication plans, so it is expected to be able to significantly increase the abovementioned numbers in the coming months. Special attention must be paid to dissemination in schools, since in everything related to environmental activities, it is important to open the way to the next generations from an early age, since it is crucial to inculcate environmental awareness, in LCA words, "from the cradle".

Table 3. The academic articles published from the NEPTUNUS project at the time of writing.

Article No.	Reference	Title	Keywords
1	[100]	Addressing challenges and opportunities of the European seafood sector under a circular economy framework	Seafood, aquaculture, LCA, circular economy, climate change
2	[156]	Life cycle assessment of fish and seafood processed products—A review of methodologies and new challenges	Life cycle assessment, seafood, fisheries, nexus, environmental impacts, sustainability
3	[142]	The benefits of integrating socioeconomic dimensions of circular economy practices in the seafood sector	Circular economy, seafood sector, socio-economic dimension, bibliometric analysis
4	[157]	Evaluation of the environmental sustainability of the inshore great scallop (<i>Pecten maximus</i>) fishery in Galicia	Environmental impacts, fisheries, gastronomic product, industrial ecology, life cycle assessment, seafood
5	[158]	Towards a water-energy-food (WEF) nexus index: A review of nutrient profile models as a fundamental pillar of food and nutrition security	Diet quality, nutrition value, food analysis, dietary assessment, public health, sustainability
6	[159]	Multi-product strategy to enhance the environmental profile of the canning industry towards circular economy	Life cycle assessment, canned tuna, value chain, valorisation, by-products
7	[160]	Designing environmentally efficient aquafeeds through the use of multicriteria decision support tools	Sustainable aquaculture, aquafeed, life cycle assessment, nutrition, machine learning, seafood
8	[161]	The fishing and seafood sector in the time of COVID-19: Considerations for local and global opportunities and responses	Seafood, COVID-19, SARS-CoV-2, fisheries, pandemic
9	[67]	Packaging environmental impact on seafood supply chains: A review of life cycle assessment studies	Canning, fish, food packaging, industrial ecology, life cycle assessment, plastic
10	[138]	Empower Eco multiactor HUB: A triple helix ‘academia-industry-authority’ approach to creating and sharing potentially disruptive tools for addressing novel and emerging new Green Deal opportunities under a United Nations Sustainable Development Goals framework	Just transition, New Green Deal, sustainability, open research, multiactor hub, circularity, UN Sustainable Development Goals
11	[71]	Life cycle inventory of plastics losses from seafood supply chains: Methodology and application to French fish products	Life cycle assessment, marine debris, plastic pollution, lost fishing gears, microplastics, macroplastics

6. Expected Outputs and Conclusions

The NEPTUNUS project provides an opportunity to contribute to a European CE strategy, addressing the three key aspects of sustainability: economy, society, and environment. The expected results of NEPTUNUS will help to promote responsible production and consumption of seafood products by identifying the main barriers, challenges and solutions for the fishing and aquaculture activities in the AA and defining strategies based on a life cycle-thinking, water-energy-food nexus and a CE, in line with the upcoming ‘circularity revolution’, which will promote economic growth in the AA.

Taking an approach that addresses both production and consumption gives the project the advantage of understanding the key points for minimizing and recovering food waste, thereby promoting the responsible and sustainable use of natural resources. Furthermore, by addressing a CE perspective, where waste is minimised as much as possible and unavoidable waste is converted into new value-added resources, it opens the door to an innovative approach to the age-old problem of seafood waste.

Due to the great importance of fishing and aquaculture activities in much of Europe, this project offers the opportunity to improve fish production, providing social benefits, such as job creation, and economic benefits, such as value creation. From an economic point of view, the transition from a linear to a circular economy, or in other words, closing the loop, contributes to strengthening the sector by obtaining products with higher added

value and savings in the final or end-of-life management of waste. On the other hand, the social relevance is also significant, highlighting the promotion of sustainable development, in which FLW occupies a key position, the need to mitigate and adapt to climate change, the importance of stimulating regional maritime zones and of addressing food security as a priority problem. Indeed, capitalisation is one of the main drivers of NEPTUNUS, which couples long-term methodologies by the definition of strategies and short-term regional case studies. Dissemination activities and networking with all the stakeholders involved in the seafood supply chain are key for the achievement of the project objectives. It is envisaged that the framework, tools, and policies that were collaboratively developed and validated during this project will continue to be used long after it is completed.

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