BlueRev

Bio-based revitalisation
of local communities

Life Cycle Assessment of marine resource use in three European regions and effects of increased byproduct utilisation

Deliverable 3.5

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Table of Abbreviations and Acronyms

Abbreviation	Meaning
LCA	Life Cycle Assessment
GWP	Global Warming Potential
MGO	Marine gas oil
GHG	Greenhouse gas
CO_2 eq.	Carbon dioxide equivalents
Carbon footprint	GHG emissions of a product or service

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1 Executive Summary

The BlueRev project aims at revitalising coastal communities in Europe through the development of a sustainable blue economy. To achieve this, regional marine resources are to be used in both traditional and new ways to establish a bio-based economy which is both environmentally and economically sustainable. Within the project, three pilot regions (Estonia, Italy and Denmark/Greenland) are assessed using governance analyses, business models, social innovation and sustainability analysis to ensure a holistic picture of the current status and develop efficient pathways towards a sustainable bio-based economy.

This study is focussing on the environmental sustainability of marine resource use in the pilot regions with the goal of supplying a complementary perspective to the work on social and governance conducted in the project. In each pilot region, a case study of marine resource use was analysed using life cycle analyse (LCA) focussing on the greenhouse gas (GHG) emissions of current and potential future production of marine foods and products. By quantifying GHG emissions, a comparison of current practises and potential future production is possible and through the identification of emission hot-spots, concrete improvement actions can be identified.

The following products were analysed in the different pilot regions:

- *Estonia*: Furcellaran from fished or farmed red seaweed
- *Italy*: Co-production of canned tuna loins and bottarga (cured tuna roe)
- *Greenland*: Atlantic cod filets and potential byproduct uses

Results from the LCA showed that the fishing stage of the production system contributes the most to the carbon footprint of the different products produced today. The use of farmed instead of fished seaweed was identified as an improvement option for the Estonian case study, due to the lower GHG emissions of farming operations compared to fishing. The Italian case study showed the importance of method choice in LCA analyses of production systems with byproducts (like tuna trimmings) and in the Greenland case study the lowering of carbon footprints through increased byproduct utilisation could be demonstrated.

2 Introduction

2.1 Context overview

The project Bio-based revitalisation of local communities (BlueRev) has received funding from European Union's Horizon Europe Research and Innovation programme under GAP-101060537. The overall concept of BlueRev is centred around revitalisation of European local communities in the form of innovative bio-based business, governance models and social innovations related to the blue bio-based sector, demonstrating the benefits the wide deployment of the bio-based economy can offer. The project rationale builds on the foundation of the EU Blue Growth strategy (EC 2012) and subsequent strategy and roadmap documents identifying the potential of the blue bioeconomy on both international, national and regional levels (Beyer et al. 2017, EC 2023).

While fisheries and aquaculture are traditional and important food producing sectors both in Europe and elsewhere, considerable development potential exists in terms of contribution to food and nutrition security and optimized utilisation from produced biomasses (e.g., Ghaly et al. 2013). Edible yield of aquatic species spans from 10% (e.g. bivalves such as oysters, scallop) of liveweight to 70% (e.g. cephalopods such as squid and octopus) – or even higher when it comes to seaweed, where only a part of the stem is not considered directly edible. The bulk of seafood consumed, however, fish and crustaceans, have an edible yield of between 30 and 60%; the remaining 40-70% of the biomass is predominantly not used for food. The large volumes have spurred the interest in better utilization, especially due to high nutritional value of the side streams (in some cases higher than the fillet main product, FAO 2018), increasing competition for high-quality biomass for food and feed- and not the least the low economic margins in the seafood industry where added value creation of side streams may improve competitiveness.

At present, most seafood processing side streams are, at best, used to produce fish meal and oil (e.g., Myhre et al. 2023). Even this utilization is sometimes logistically challenging due to the location and volume of some supply chains (e.g. cod landed in many small ports along the Norwegian and Greenland coast). When the generation of seafood side streams is larger and more concentrated (e.g. large-scale processing plants for shrimps or slaughter plants for farmed salmon), the conditions to achieve a higher degree of utilisation and value creation are better; the side stream can in these cases be a part of the business from start. Given the high competition and low financial margins in the seafood industry, even a small increase in value of the side streams can, based on the large volumes, represent a critical contribution that can shift red to black figures for an entire business.

Increased utilisation and value creation from seafood side streams represents not only a possibility to create new products from resources already extracted/produced that can replace less sustainable products used today. It can also contribute to a more economically sustainable seafood sector, which can allow the seafood sector to expand and innovate more than today. Considering dietary recommendations in many countries to eat more seafood and less other animal-sourced foods, from health and sustainability perspectives, while resources are limited and often dependent on imports (Thurstan & Roberts 2024), increased valorisation of seafood side streams could facilitate this important dietary shift. Wasting less resources also contributes to lower-impact seafood.

In BlueRev, three European regions with an identified potential to develop the blue bioeconomy, including through increased side stream utilization, participate:

- Sicily, in southern Italy
- Saaremaa island, on the Baltic coast of Estonia
- Greenland, in commonwealth of Denmark

Each of these regions have traditional and important industrial sectors building on the extraction and processing of marine biomass and see the potential to further develop the activities to generate more societal benefits from these limited marine resources, motivating participation in the BlueRev project. In order to make sure that future supply chains are more sustainable than today, it is however important to be aware about environmental consequences of different strategies. For that purpose, an objective assessment is needed to evaluate environmental impacts of current vs. future products and their supply chains.

2.2 LCA overview

A widely used, science-based and recognised internationally standardised method for the environmental assessment of products and product supply chains is Life Cycle Assessment (LCA) (ISO 2006 a, b). LCA is often used to identify environmental hotspots and improvement options in product supply chains, or to compare products or production methods, from an environmental point of view, including seafood (Bohnes et al. 2019; Ziegler et al. 2016). Other uses include as a basis for environmental labelling or communication with customers and as a basis for private or public decision-making about investments or regulations. The assessment shall cover “all relevant environmental aspects” as well as define the system boundaries of the supply chain studies in a way that avoids tradeoffs, i.e. shifting burdens between different life cycle phases or environmental impact categories.

The undertaking of an LCA consists of four steps, often performed in an iterative process. In the first step, Goal and Scope, many important methodological decisions are taken such as defining the goal of the study and the product to be studied (the ‘functional unit’). It also defines to which point in the supply chain the product will be followed and what activities to include/exclude (the ‘system boundaries’). A number of other important specific method choices also need to be made such as which types of environmental impact to assess (e.g. acidification, toxicity, eutrophication, global warming). Often, there is a need to distribute impacts of a production system amongst various co-products ('co-product allocation'); examples from seafood production include the fishery where several species are landed together, or in processing, when several edible and non-edible co-products are generated simultaneously. The specific methodological choices made in this stage can have a major impact on results, why these need to be presented and justified in a clear way.

After Goal and Scope, the step to collect data follows, Life Cycle Inventory (LCI). It involves collection of data on material and energy use and generation of waste for each step in the supply chain. For each process, *inputs* in terms of material and energy use are quantified in relation to *outputs* (products, waste and emissions). The LCI is a critical step of LCA performance since the reproducibility, consistency and precision of the data collected determines the quality of results. It is also the most time-consuming step.

The third step is Impact Assessment. All quantified flows are summarized over the supply chain. Resources used and emissions generated are categorised and grouped according to the types of environmental impacts they contribute to. The fourth and last step of performing an LCA consists of analysing and interpreting results. Sensitivity and uncertainty analyses are carried out to see how robust results are to data variability, important assumptions or methodological choices. As a result, earlier steps may need to be revisited (e.g. more data may need to be collected) before the model is finalized, thus the need for an iterative process. For more details on the LCA methodology, see Baumann and Tillman (2004) or ISO (2006 a, b)

Here we undertake an LCA study of alternative uses of one aquatic biomass generated in each of the three study regions to provide a basis for discussions about continued regional development based on these resources. The cases were selected by the regional representatives, who also represented the link to the companies. Results can be used to explore consequences of increased byproduct utilisation or use of novel, underexploited resources. It is important to note that information resulting from an LCA needs to be seen in a wider perspective, i.e. if environmental sustainability goes hand in hand with social and economic sustainability, governance aspects studies in other parts of the project. Hence, an LCA will not give a simple answer for regions on which way to go, but rather give environmental decision-support to the decision-making process.

3 Goal and Scope

3.1 Goal

The goal of the LCAs undertaken within the BlueRev project is to add a complementing environmental perspective to the work on governance and social aspects conducted in the pilot regions by providing insight into the environmental impacts of current and future (potential) use of marine resources. Results from this study will provide insights into the environmental performance of current production systems, existing hotspots and explore improvement potentials through scenario analysis.

3.2 Case study selection and data collection process

Case studies in this report were selected by the pilot region lead for the three assessed regions, in collaboration with the involved companies and the LCA practitioners (authors of this report). To secure alignment with the BlueRev projects goals and framework, while also ensuring feasibility of the LCA analysis, the following selection criteria were outlined:

The production represents a potential for increased side stream utilisation and valorisation of marine resources.

The data required -both for the production of the raw materials (from literature) and for their processing into more high-value products- were feasible to obtain by the pilot region lead, the companies and the LCA practitioners.

The data for the analysis presented in this report was collected during 2023 and 2024. Data collection was in all cases initiated with a meeting with the pilot region lead in the project who then identified a case study and data sources. The data collection process proved to be easier in some regions than in others and data availability strongly influences what is possible to analyse. The detailed data used for modelling is collected in Annex I, II and III. However, due to confidential industry data, not all data is included in the public report. Below the data collection process is outlined in more detail for the different regions:

Estonia

Initial planning was done with the pilot region coordinator. A company processing locally harvested seaweed into extracts used in food and cosmetic applications was identified as the focus of LCA. This was motivated from their unique use of marine resources and important role within the blue bioeconomy on the Estonian island Saaremaa. The company was presented with general information about the BlueRev project and the expected data needs and potential outcomes of an LCA analysis. The company had recently finished an LCA in cooperation with an Estonian researcher who was not involved in the BlueRev project. The pilot region coordinator made efforts to get access to this LCA, to establish the current level of knowledge and access to important input data but ultimately he was unable to access the documentation and results of this external LCA. In parallel, efforts were made to collect seaweed harvesting and processing data from the company via spreadsheets and questionnaires in the same way as in the other two pilot regions. Data collection efforts were ongoing during mostly autumn 2023 and no sufficient primary data could be attained. Therefore, it was decided to perform a literature based LCA of wild harvested seaweed used for extract production, compared to a theoretical farmed seaweed used as starting biomass in the extraction process. While the analysis is based on generic data taken from scientific publications and LCA databases, potentially increasing the error margin of results, results can be useful to identify trends and general conclusions of potential future biomass production in the Saarema region of Estonia.

Greenland/Denmark

The data collection process was initiated by meeting with the pilot region coordinator to explore possible cases for the LCA. The options presented were a unique cod fishery and processing technique in Greenland or a whitefish fillet processing variant which allows for reuse of side streams in Denmark to produce nutraceuticals, flavouring ingredients or to enrich the nutritional properties of whitefish filets through injection. The Greenland case was prioritised due to better predicted data availability based on good connections with the producing company. It was well matched to the BlueRev project goals though the analysis environmental impact reduction potential when more side products are utilised for food/feed or other applications. To analyse the fishing and processing operations, mostly technical data in the form of e.g. energy use or transport distances was collected by the producing company using a spreadsheet. The data was collected predominately during late 2023 with minor corrections and additions in early 2024. The collected data was verified with the company representative in reoccurring online meetings.

Italy

Data collection was initiated in a meeting with the pilot region coordinator and two possibilities for LCA analysis were presented. One focusing on lab scale use of fishery byproducts for fish feed production and another one focussing on the use of tuna byproduct (tuna roe) to produce a local delicacy, bottarga, at a tuna canning facility. Motivated by being a larger scale and established production, the bottarga case was chosen. This case study was relevant not only since it investigated the use of byproducts for value-added food product. It also focusses on a food product with long history in the region, highlighting that byproduct valorisation does not necessarily depend on modern processing techniques to produce high-value products.

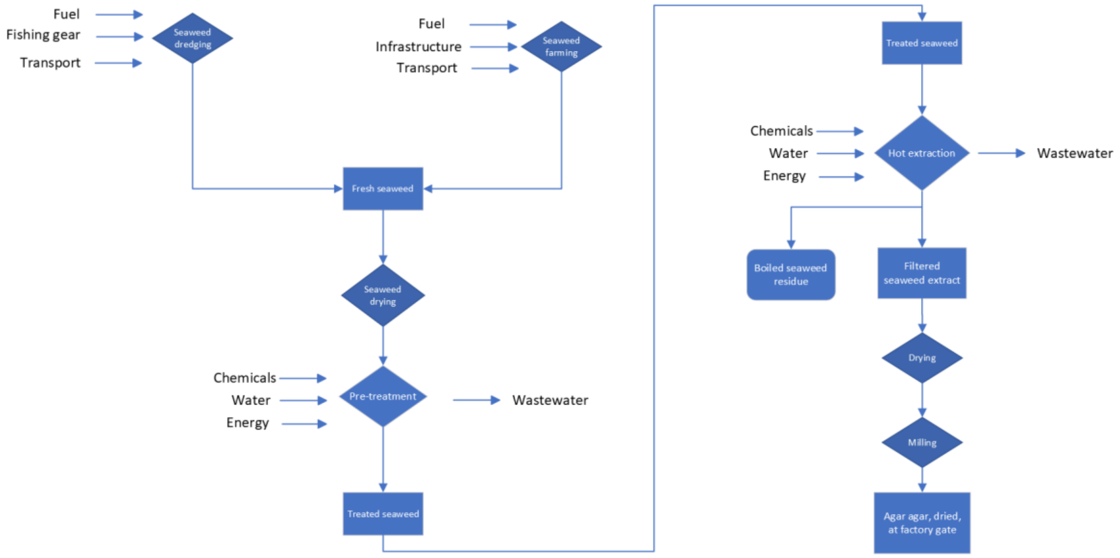
Data collection was facilitated by the case study coordinator through a series of meetings, both with and without the LCA team, where predominately processing data for the tuna canning facility was collected in a spreadsheet. Data collection was conducted from late spring 2023 to early 2024 with the main part of the data being collected in the fall.

3.3 Description of case studies

3.3.1 Case study: Estonia

Estonia has a long tradition of fishery and use of marine resources from its coastline and archipelago in the Baltic Sea. This project focuses on the island Saaremaa, located in the western part of the country along the Baltic coast. On this island, the seaweed *Furcellaria lumbricalis* has been used for decades to produce the gelling agent furcellaran. The seaweed is harvested either from beachcast (algae naturally deposited at shores) or “fished” using a dredge in shallow waters around the island. While this seaweed species also occurs in other countries around the Baltic and in the North Atlantic, it is rarely utilised as a raw material for further refinement. After a cleaning step at the factory, the fucellaran is extracted from the seaweed using heat. The resulting solution is then filtered and the fucellaran is concentrated by either roller drying or gel precipitation. The finished product is used in a variety of industries including food, cosmetics, pharmaceuticals, and packaging applications, mainly after export. In today’s production, seaweed byproducts exist in the form of the solid fraction biomass remaining after the furcellaran extraction using water and heat. This biomass is currently distributed to local farmers to be used as fertiliser.

Figure 1 describes the system boundaries of this case study and the simplified sequences of activities related to the whole process, starting from the seaweed dredging up to the active material extraction and processing, taking into consideration the energy and the material flows in and outside the system, as fuel for transportation and equipment, water for processing and waste stream to eliminate. The final product is then packaged. The present study doesn’t include shipment to different markets.

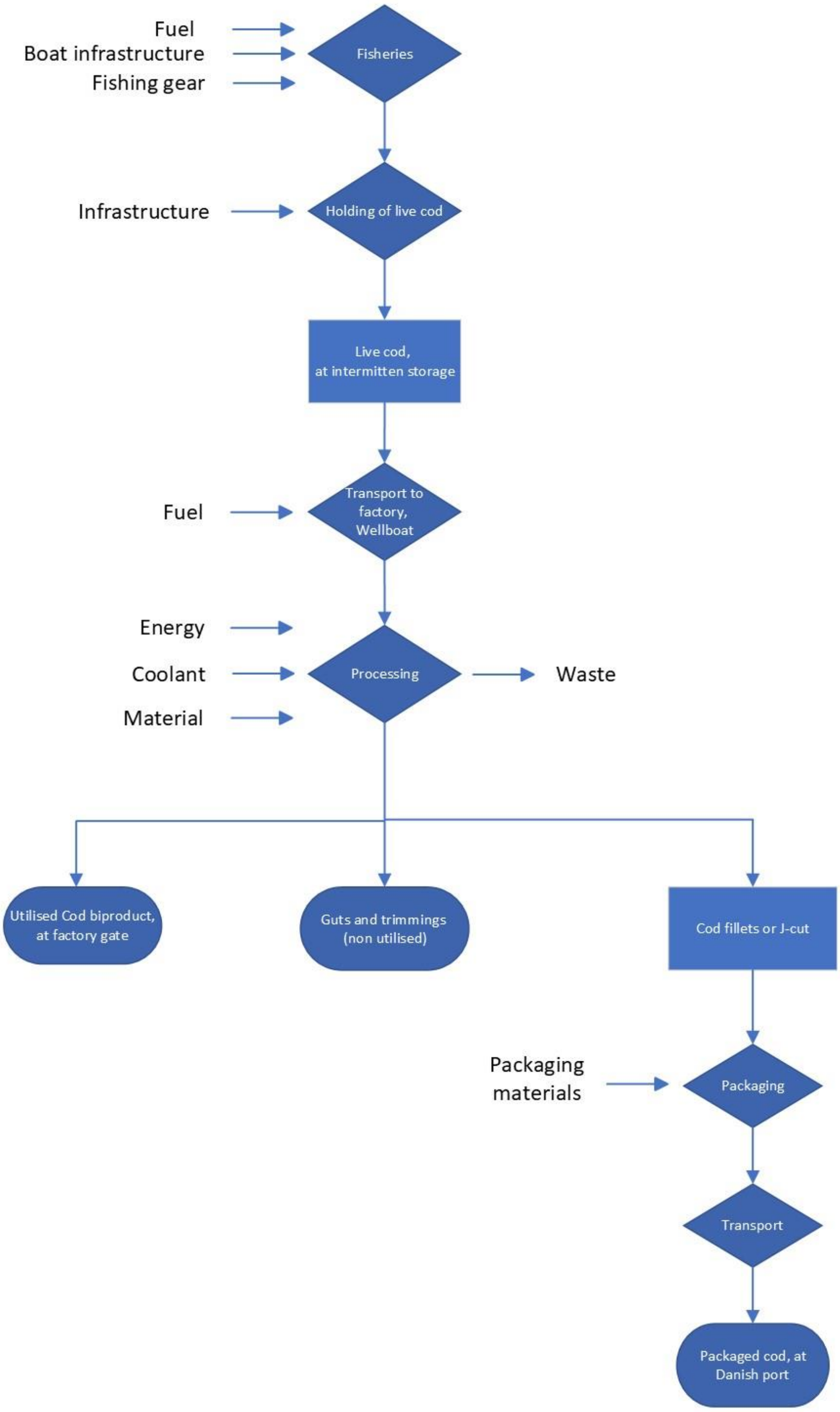


Figur 1 Flowchart of agar production from wild harvested or farmed red algae

3.3.2 Case study: Greenland

The fishing industry is of large importance in Greenland, with up to 90% of the country's export revenues comprising of fishery products. In this case study, one specific fishery is investigated for a potential increase in byproduct use and the resulting consequences for the environmental footprint of the products. The fishery is located on the western coast of Greenland and targets Atlantic cod (*Gadus morhua*) in the fjords. The fish are caught alive using poundnets. The caught fish are then stored in temporary net cages, to empty their digestive system of food residues before being collected by a wellboat. This well boat (also called transfer boat) transports the live fish to the processing factory, where they are stored in a buffer net cage again. The fish then get moved into the factory for processing into fillets, which are frozen for further transport to different markets. This treatment aims at minimising the time between slaughter and frozen filet to a minimum, and the resulting filets are branded and sold in high-end restaurants. Currently there is only limited use of the byproducts from slaughter and filleting of the cod. This is due to a lack of renewable energy for e.g. fishmeal production, manpower for further processing steps and the long transport distances required – combined making the use of byproducts unprofitable in the current marked. The non-utilised byproducts are sailed out to appointed ground by government for outlet to the sea.

In figure 2 the production process of the case study is visualised, including energy and material flows inside and outside the system.



Figur 2 Flowchart of the Greenlandic supply chain producing trap-caught cod fillets.

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3.3.3 Case study: Italy

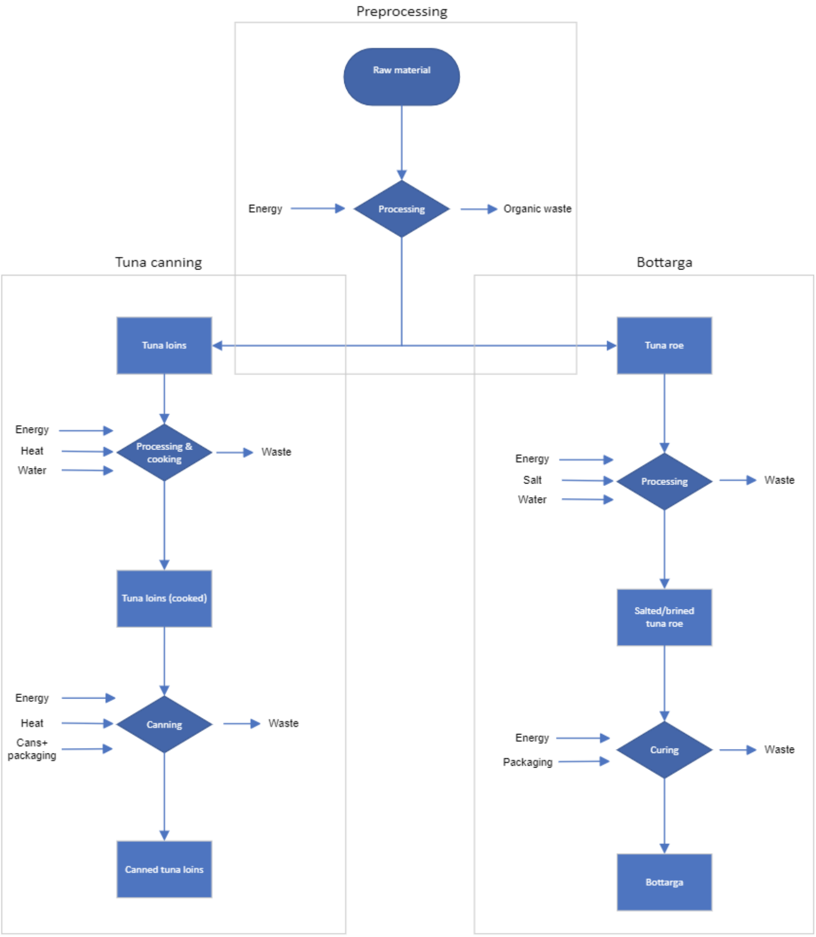
Tuna fishing and processing has a long history in Italy and specifically in Sicily, the region participating in this case study. Due to its strategic geographical position in the Mediterranean Sea, Sicily has, historically, a natural inclination towards activities related to the tuna fishing (Fontana, 2020) and tuna processing. There are numerous tuna processing companies in Sicily, some of them historical, established in the early 1900s, which still produce different formats of canned tuna using two different species (*Thunnus albacares* and *Thunnus thynnus*). Some of these companies manage to innovate production by not limiting themselves to producing canned tuna, but creating products to diversify production, such as tuna salami or bresaola.

Tuna fisheries are connected to large quantity of side streams generated during the pre-processing and processing stages. The systematic utilization of side streams generated has been identified as being essential to make sure the significant quantity of nutritional components is available for the consumers in the form of value-added products (Sasidharan et al., 2023). The identification of technologies to obtain products from tuna waste can help the industry to adopt the optimum process according to the type and quantity of their side streams. Adding such technologies into the production process can ultimately result in more economically circular and sustainable tuna fisheries (Sasidharan et al., 2023).

Tuna processing industry in the province of Trapani, has a fundamental economic and social importance, with historical companies and a nationally significant production of processed tuna. Even today, although the amount of tuna caught in the province of Trapani has decreased, the significant development of fish canning companies contributes to that tuna continues to be a product of considerable economic importance. Canning industries implement different processes of tuna processing with production of processed salted, smoked, cooked and preserved in oil (Istituto di Biologia Marina di Trapani, 2007). Today, much of the tuna used is imported pre-processed from fisheries in the pacific or Indian ocean.

In particular, for tuna processing companies in Trapani and Palermo, the largest ones in the Sicilian territory, quality of the raw material at origin and the maintenance of the same throughout the supply chain are requirements of primary importance, if local productions of canned tuna in oil and in its natural state are to be kept distinct and identifiable. Additionally, traditional local products such as bottarga, heart, mosciame, tuna salami and bresaola are produced, which are particularly appreciated in the domestic and foreign markets and have a high commercial value (Istituto di Biologia Marina di Trapani, 2007).

Bottarga is a cured product, a relish made of roes of tuna that is lightly salted, pressed and sundried. It can be used fresh or stored up to 3 years. From a regional food status of Sicily, bottarga has been gaining a wider recognition during last time (Garaffo et al., 2011). Consumer demand for natural and nutritious processed fish products is gaining more attention, which drives opportunities to add commercial value and improve the functionality of unprocessed roe. Therefore, the development of technologies to characterize compounds, including physicochemical properties of this product from fish processing, is relevant and brings great value (Bunga et al., 2022).



Figur 3 Flowchart of the Italian supply chain for the production of tuna loins and bottarga from imported yellowfin tuna

3.4 Scope

3.4.1 Functional unit (FU)

Estonia

The production of furcellaran from either dredged or farmed red algae was analysed using the functional units (FU) *1 kg furcellaran, produced from dredged seaweed* and *1kg furcellaran, produced from farmed seaweed*.

Greenland

One main and one intermittent FU were analysed. The main FU is *1kg of cod filet, packaged, at Danish port* whereas the intermittent FU of *1 kg cod, live, at processing plant entry* was used to analyse the fishing stage of the production system.

Italy

The parallel production of two tuna products is analysed. The two FUs used in this study are *1 kg canned tuna, packaged, at factory gate* and *1 kg bottarga, packaged, at factory gate*.

3.4.2 Temporal scope

Estonia

The temporal scope of this analysis is not set to specific years as there was no collection of primary data. The analysis aims at representing current day production of furcellaran.

Greenland

The temporal scope is 2022 and 2023, based on the primary data available.

Italy

The analysis is based on primary data for the years 2021 and 2022.

3.4.3 Geographical scope

Since the BlueRev projects focus is on revitalising local communities, the geographical scope of the case studies is confined to the investigated pilot regions Greenland (west coast), Italy (Sicily) and Estonia (Saaremaa).

3.4.4 Allocation

Allocation describes the division on environmental burden from e.g. processing operations, if more than one product is produced. This division can be based on different attributes of the products in question and allocation based on physical properties (mass, protein content etc.) or economic value are most commonly used. In this study, mass

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allocation is used unless otherwise stated following the methods described in ISO 14040/44 (ISO 2006a,b).

3.4.5 Impact assessment method

Although a multitude environmental impact categories exist in LCAs, this analysis was limited to a carbon footprint in the form of the global warming potential (GWP) of the investigated production systems. Many environmental challenges exist for seafood production, including risks for overexploitation of target species and various biodiversity pressures, the focus of BlueRev is primarily related to changes made post-harvest. This calls for investigation of environmental impacts that have the potential to differ within the production systems, where greenhouse gas (GHG) emissions are highly relevant. Furthermore, the opportunities to include other impact categories were limited in terms of available data from the pilot regions. The results were expressed in kg CO_2 equivalents and calculated using the "IPCC 2021 GWP100" impact assessment method. This method is based on emission factors from the sixth IPCC assessment report for global warming (IPCC 2023) and represents the industry standard for carbon footprint calculations.

4 Life Cycle Inventory (LCI)

As all three case studies differ from each other in multiple technical aspects (processing, data collection, processes and raw materials included, product form and alternative byproduct uses identified), extensive technical information had to be documented. Three shorter sections detailing the data and some modelling choices in the different case studies have been included as appendixes.

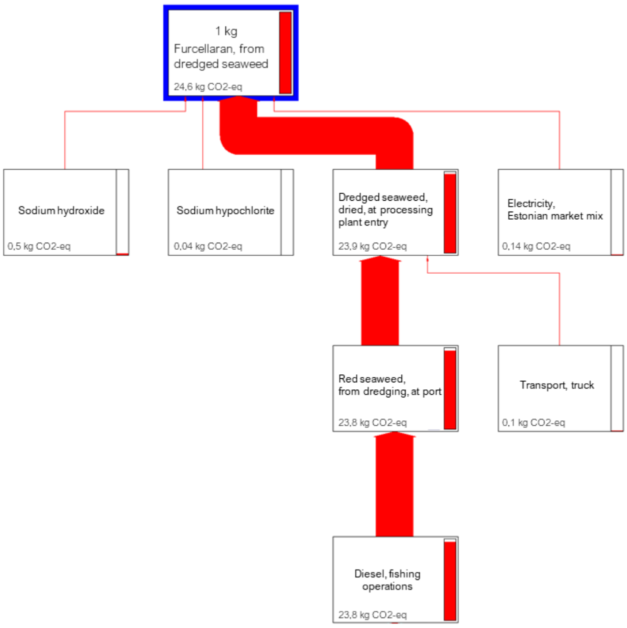
5 Life Cycle Impact Assessment (LCIA)

5.1 Results of case studies

Estonia

This part of study focuses on theoretical comparison of dredged and farmed red seaweed as raw material for furcellaran production in Estonia. This scenario is purely based on literature values and assumptions, which are documented in annex II, and shows a possible future scenario where seaweed farming becomes a valid alternative to current seaweed dredging practises.

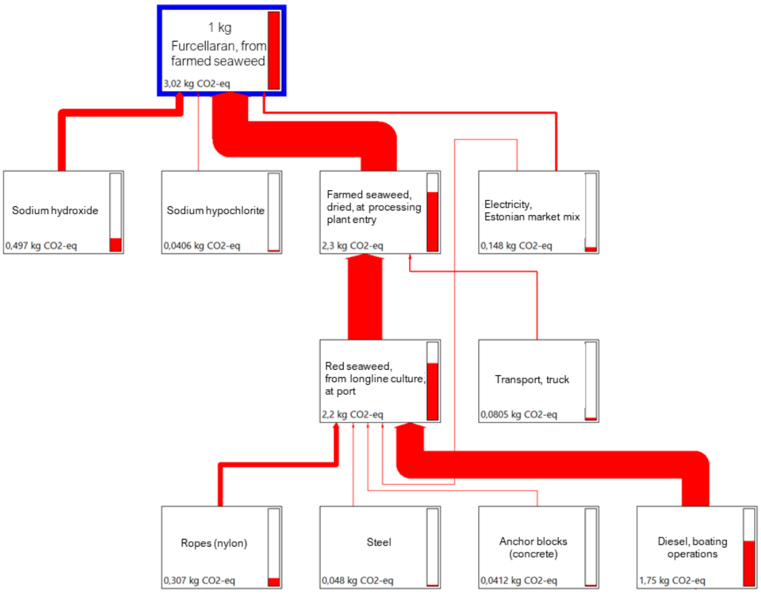
In the current production system, the seaweed for furcellaran production is sourced from both dredged and beach-cast seaweed. The dredged seaweed is fished by a local fisherman and stand for roughly 25% of the yearly processed volume. The remaining 75% percent are provided by local inhabitants, which collect the beachcast seaweed and dry it before delivery to the processing plant. Due to a lack of data for transport modes, yields and distances of the beach-cast collection, this option was excluded from the analysis.



Figur 4 Global warming potential of 1 kg furcellaran, produced from dredged seaweed

Per kilogram of furcellaran produced from dredged seaweed, 24.6 kg CO_2 eq. are emitted. The GHG emissions of dredged seaweed based furcellaran are dominated by the fuel use during fishing operations and other processing inputs during the extraction process, transport or energy use at the factory only contribute marginally (Figure 4). Dredging is a fuel intensive fishing method due to the high resistance of the fishing gear used, leading to the high fuel use, and subsequent high emissions, for this harvesting option. Fresh weight, dredged seaweed at landing has a carbon footprint of 1.3 kg CO_2 eq. per kg seaweed but because of the drying step and furcellaran yield of 29%, multiple kilos of fresh weight seaweed are needed to produce 1 kg of furcellaran.

Estonia – Scenario analyse

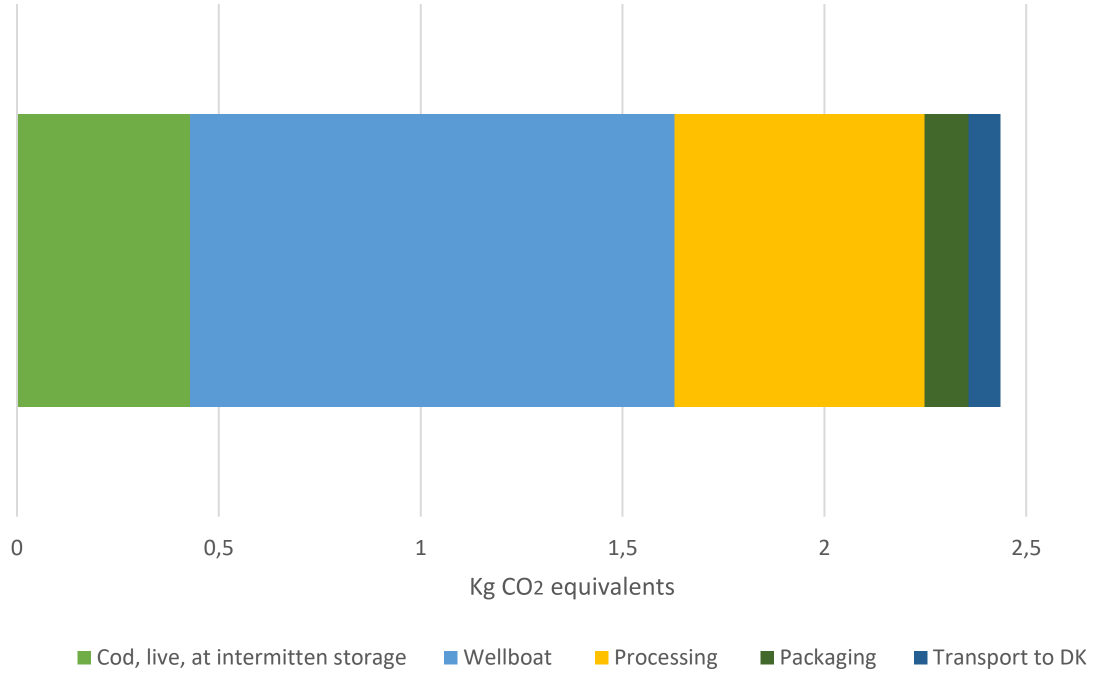


Figur 5 Global warming potential of 1 kg furcellaran, produced from farmed seaweed.

Furcellaran from farmed seaweed has a roughly 8 times lower GHG emissions than dredged based furcellaran at 3.0 kg CO_2 eq. per kg product. Similar to the dredged seaweed based furcellaran, the seaweed biomass is the most important contributor to the total carbon footprint at 76% of total emissions. For the farmed seaweed biomasses, the GHG emissions related to the fuel use during boating operations are the largest contributor, followed by the production and use of nylon ropes in the farming infrastructure (Figure 5).

Greenland

The main functional unit analysed in this study is *1 kg of cod filets, at Danish port*. Additionally, the intermediate functional unit of *1 kg live cod, at factory entry* was used to analyse the fishery in further detail. Below, the total GHG emissions and individual process contribution to the main functional unit is visualised in figure 6.



Figur 6 GWP of 1 kg cod filet (packaged), at port in Denmark and contribution of different processes in the production system.

At port in Denmark, 1 kg of cod filet from the investigated fishery and processing operation has a carbon footprint of 2.44 kg CO_2 equivalents. The most important contribution to the carbon footprint is fuel use during the fishing stage, with both fishing operations, intermittent storage and wellboat transfer to the processing facility. The processing operation account for 25% of the total GHG emissions, with the electricity use at the processing plant being a hot-spot due to the electricity source (fossil fuel based). Packaging and transport from Greenland to Denmark only contribute marginally, at 5% and 3% of the total carbon footprint respectively.

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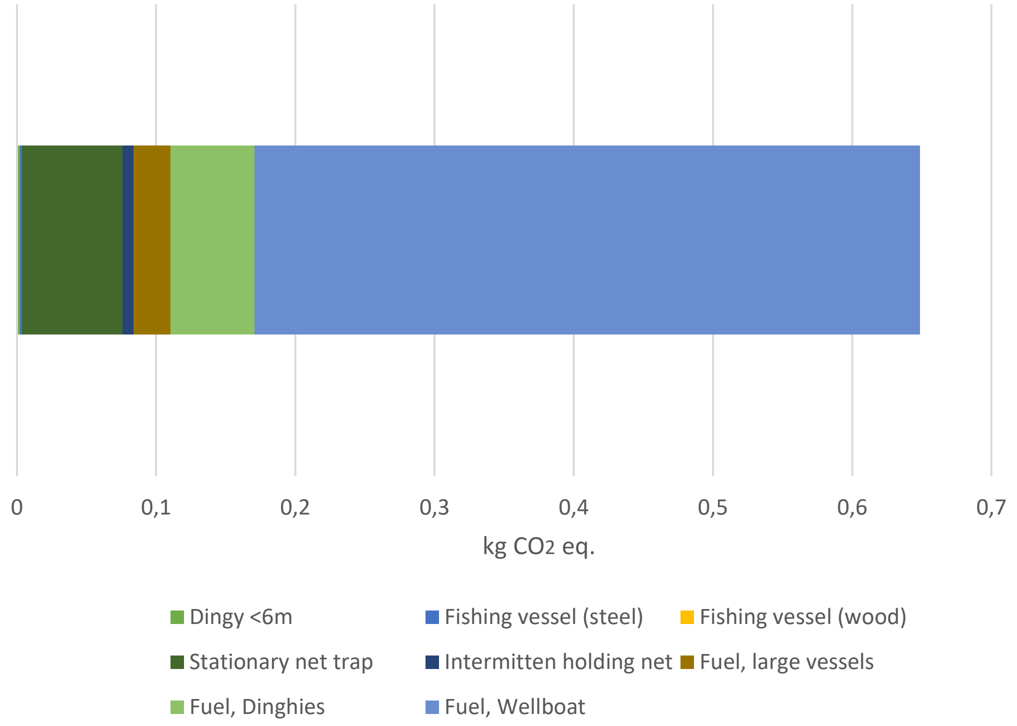

Figur 7 GWP of 1 kg live cod, at processing factory entry and contribution of different processes in the production system.

When further investigating the fishing stage it becomes clear that wellboat operations dominates the total carbon footprint of 0.65 kg CO_2 eq. for 1 kg of live fish, at processing factory entrance (figure 7). The wellboat transfer stands for 74% of the fishing stages emissions, driven by use of fossil fuel based MGO and comparatively high fuel use of the vessel. Furthermore, due to the needs to transport live fish, the vessel has large amounts of seawater and fish “loaded” in internal tanks, leading to a large weight being transported. Additionally, the wellboat has to serve a total of 325 intermittent storage nets spread throughout the fjords surrounding the processing plant, leading to large transport distances.

Fuel use for the larger fishing vessels and dinghies used in the fishery stands for a combined 13% of the total carbon footprint whereas the contribution of materials used in the construction of these boats on contribute marginally at a combined value of 0.6%, taking into consideration boat lifespan.

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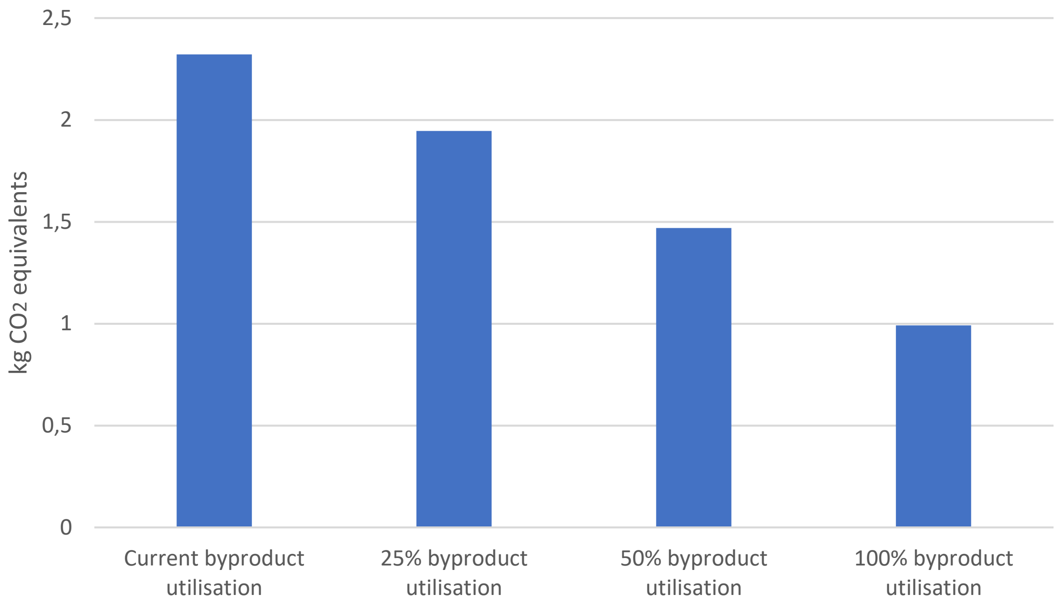
Greenland – Scenario analysis

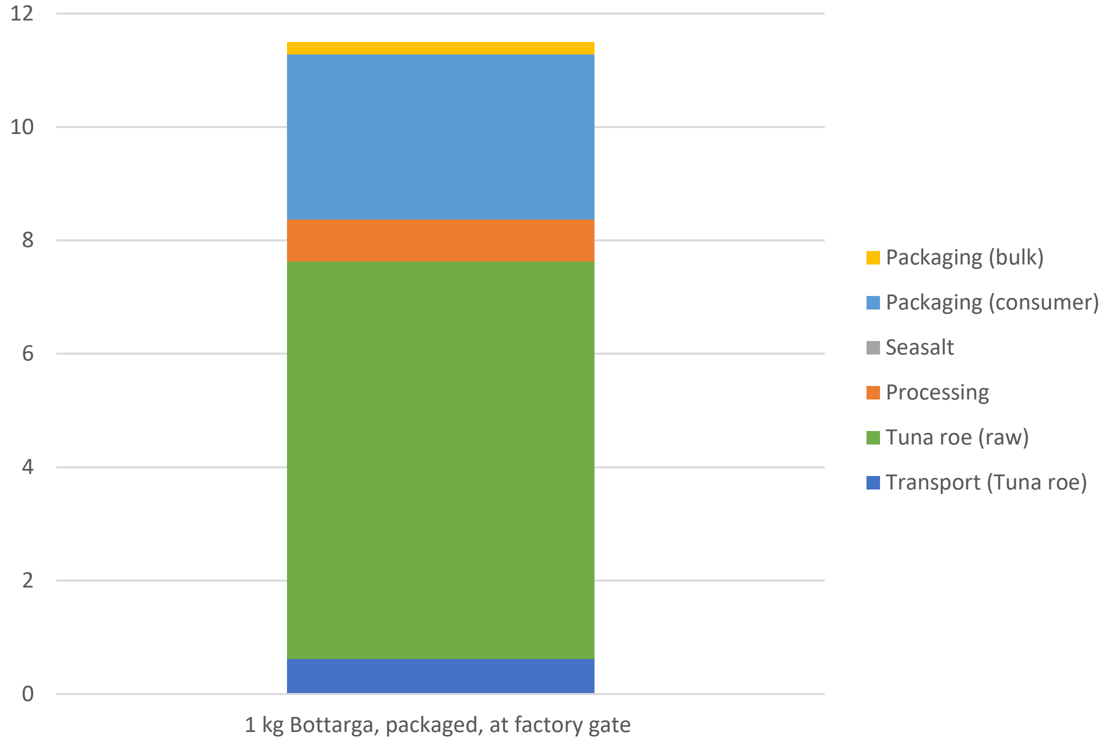


Figur 8 Carbon footprint of 1 kg cod filet, unpackaged, at factory gate when applying different levels of byproduct utilisation as a scenario analysis.

Currently, only a fraction of byproducts from the cod processing plant are being further utilised and sold. Today's use cases for the byproducts are the sale of fresh or frozen cod heads for further processing, and sale of block frozen skin. Even the sale of cod roe is done depending on market price and processing capacity. Figure 6 depicts the effect of increasing byproduct utilisation on the carbon footprint of *1 kg cod filet, at factory gate,* from the current level of 13% to the theoretical utilisation of all byproducts. While utilising all byproduct from processing is unlikely, a doubling of currently utilised volumes to reach a level of 25% utilisation already contributes to a significant reduction of the carbon footprint and improved resource utilisation (Figure 8). The feasibility of this is further described in the discussion.

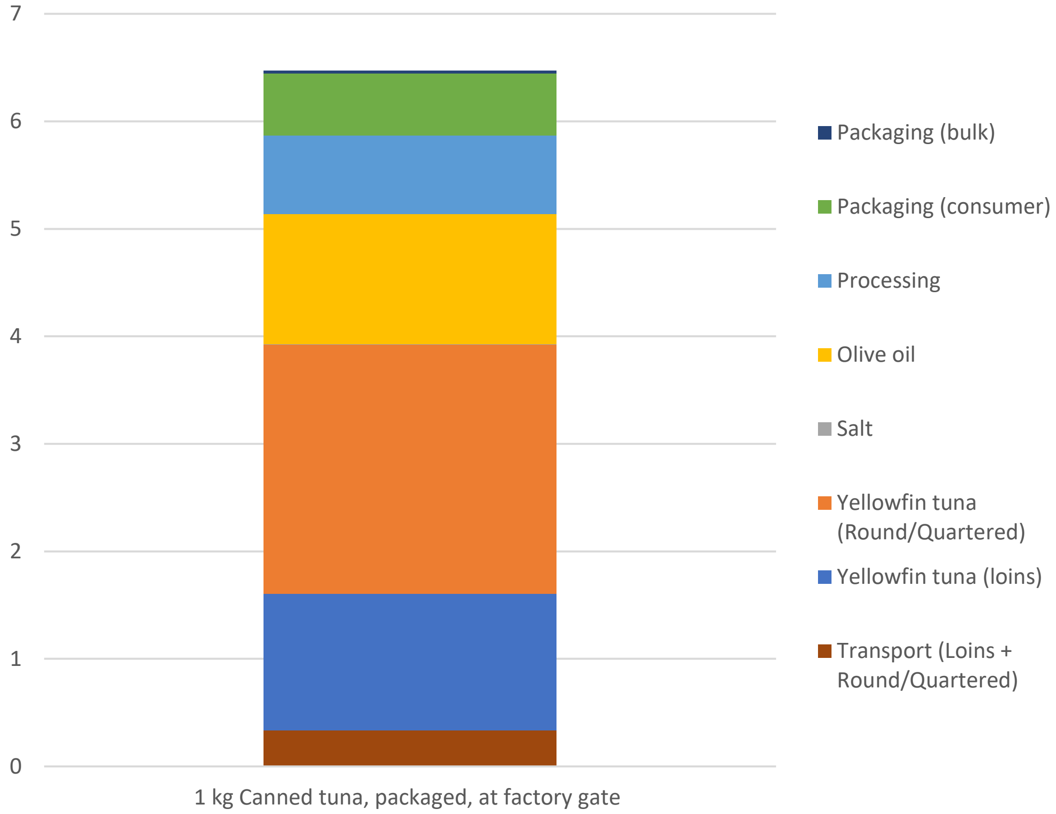
<u>*Italy*</u>

The focus in analysing the Sicilian case study was laid on the tuna canning and bottarga production at the same factory. The investigated functional units are therefore *1 kg canned tuna, packaged, at processing plant gate* and *1 kg bottarga, packaged, at processing plant gate*.



Figur 9 Contribution of different materials and life cycle stages to the GWP of 1 kg bottarga, packaged, at factory gate.

The finished and packaged bottarga was found to have a carbon footprint of 11.5 kg CO_2 eq. per kg product. The biggest contributor to the GHG emissions is the tuna roe at 61% of the total, with most of the emissions resulting from fisheries operations. As bottarga is a dried product, multiple kg of fresh roe is needed to produce one kilo of the final, dried product. Both transport of the raw material and processing operations are of lesser importance at 5% and 6% respectively. The consumer packaging however is an important source for greenhouse gas emissions at a quarter of total emissions. Since bottarga is a delicacy, only limited amounts of the final product are packaged in comparatively heavy glass jars. This leads to a relatively high use of glass in relation to the final product weight.



Figur 10 Contribution of different materials and life cycle stages to the GWP of 1 kg canned tuna, packaged, at factory gate

Per kg canned and packaged tuna, at factory gate, a total of 6.5 kg CO_2 eq. are emitted. The most important contributors to this total carbon footprint are the tuna loins and the round/quartered tuna at 20% and 36% respectively. Another important ingredient is the olive oil, which causes 19% of the total greenhouse gas emissions. Similar to bottarga, transport of tuna raw material stands for 5% of the GHG emissions but processing has a higher percentual share for canned tuna at 11%. The packaging in metal cans is more resource efficient and stands for 9% or 0.6 kg CO_2 eq./kg canned tuna.

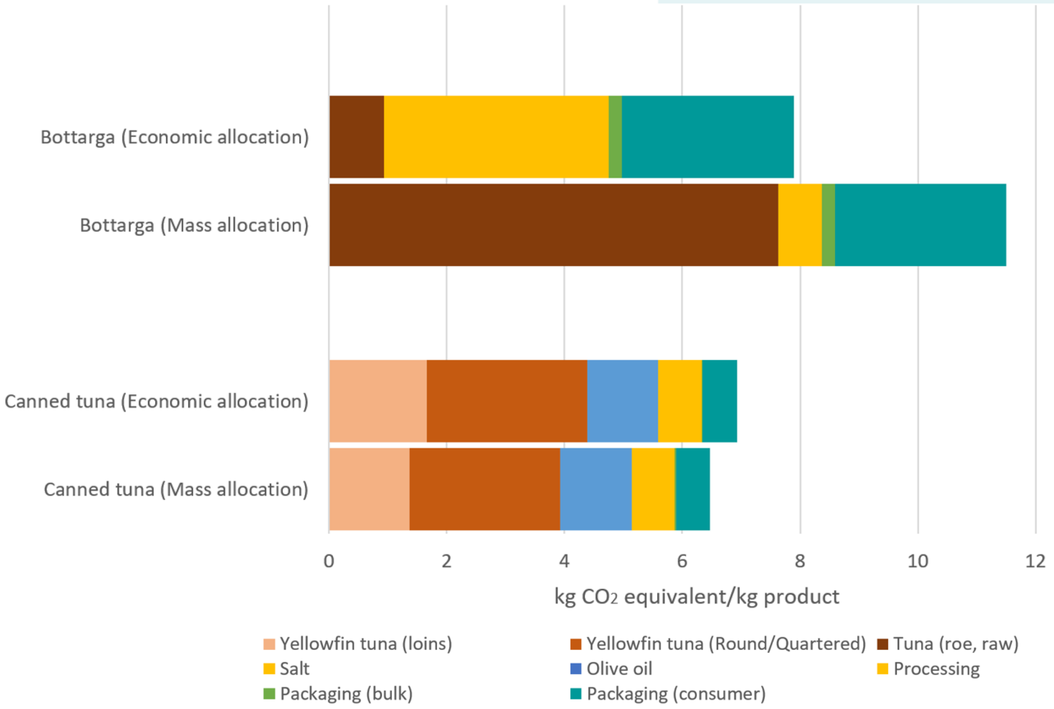
Italy – Scenario analysis

One central method decision within LCA is the basis for allocating of emissions between multiple products coming out of a single process. Within the Italian case study, there are multiple points of allocations and choice of allocation method has large influence on the final results. The first process where dividing or allocating the environmental burden between multiple outputs is needed is already at the start of the production systems. When fileting the Yellowfin tuna, different fractions or cuts are being produced. In this study tuna loins, roundcut, quartered and tuna roe are being used. In the base case analysis, the emissions connected to catching the tuna, transport to the processing plant and processing energy use are divided based on the mass of the different, utilised, cuts of fish meaning that e.g. round cut tuna is allocated 94% of the GHG emissions and tuna trimmings, which are utilised in e.g. feed for aquaculture, are allocated the remaining 6%. Waste products like non-utilised cut offs (fins, head, guts) don’t carry any of the environmental burden because these are waste streams of no monetary value.

The second point of allocation within the production system is the processing of both tuna loins and bottarga at the processing plant. Since data for energy use and other inputs can’t be divided due to e.g. a shared gas and electricity, these inputs and their connected environmental burden need to be divided afterwards in the analysis step.

The ISO standards recommend the use of physical allocation (like mass) over other forms. Dividing the environmental burden based on the monetary value of the different co-products is however also often used within LCA. This is challenging for several reasons, one being a change in price for a product will change the environmental burden – without any actual change in practice has been made. In studies like this one, where the tuna loins and round/quarters are of high value and the trimmings and organs (like the tuna roe) are of lower value, another effect of basing allocation factors on economic value are displayed clearly. The higher-value product carries almost all environmental burden and has a large environmental footprint whereas the lower-value product has a comparatively small environmental footprint, despite coming from the same raw material.

To illustrate the effects of different allocation principles, a direct comparison of both bottarga and canned tunas carbon footprint calculated with mass and economic allocation was done.



Figur 11 Comparing the contribution of material inputs and life cycle stages to the GWP of canned tuna and bottarga when applying mass or economic allocation

When analysing the global warming potential of bottarga on the basis of mass allocation, the tuna roe stands for a large part of the total carbon footprint and the processing energy and material use only contribute about 6%. When applying economic allocation to the same product, a lower total carbon footprint can be seen but also a completely turned pattern of process contribution. Since tuna trimmings and tuna roe are of comparatively low value, they have a low carbon footprint when using economic allocation and only stand for 12% of total emissions. The processing contribution has however increased to 48%. This is because bottarga has a substantially higher value per kg product and lower total amounts of annual production volumes than canned tuna and therefore takes on proportionally more of the emissions generated during the processing of canned tuna and bottarga. For the canned tuna products, the difference between the different allocation forms isn't as extreme. Since large amounts of canned tuna are produced, the difference in processing related emissions in the different allocations forms is divided over a large amount of product and the change per kg product for canned tuna is therefore small. When applying economic allocation, the tuna loins and round/quartered cuts are allocated an increased amount of the tuna raw material related emissions and therefore have a higher environmental impact (Figure 11).

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6 Discussion & Conclusion

In this study, the implications for carbon footprint for possible developments of marine resource use and byproduct utilisation in the three pilot regions have been investigated from an environmental impact perspective. Findings are intended to be used as complimenting information to the socio-economic and governance analyses done within the BlueRev project and contribute to a more holistic understanding of sustainable development. On note, the environmental dimension of seafood production comprises of more issues than carbon footprints, such as sustainable utilization of target species and various pressures on marine biodiversity. These issues where not handled here but needs attention for value chains base on in particular wild-capture resources. The focus of the LCAs was set on different aspects of production as it looks like today and future development in terms of implications for the carbon footprint, guided by regional conditions and data availability.

Estonia

The LCA results from the analysis of alternative red seaweed production methods compare to traditional dredge fishing on the Estonian island of Saarema indicate that the traditionally dredge fishing has a higher carbon footprint than the theoretical, farmed production of the same species. This higher carbon footprint multiplies throughout the production process of the seaweed extract furcellaran, as considerable volumes of wet-weight seaweed are needed per kg produced extract.

While the seaweed farming example analysed in this study is purely theoretical, seaweed production Europe is a growing sector (Araújo et al. 2021). There are multiple LCA analyses indicating that commercially farmed seaweeds are a raw material with comparatively low carbon footprint as well as small overall environmental impacts in other important areas of environmental impacts like eutrophication, acidification and land use (Thomas et al. 2021). Seaweed farming in the Baltic Sea is currently confined to a handful of farms in Danish or German waters mostly farming sugar kelp (*Saccharina latissima*) and no known cultivation of Furcellaria species is done currently (Kulikowski et al. 2021). Other red seaweed species are commercially farmed globally (e.g. *Gracilaria sp.*) but the suitability of Furcellaria for seaweed farming is unknown.

Dredging for seaweed is likely to be fuel intensive and thereby a carbon footprint intensive production method. Primary data for this fishery is unavailable for both the Estonian fishery and other seaweed dredge fisheries globally, why this study had to use literature data and assumptions. The fuel use data used in this study was based on a multitude of finfish and bivalve dredge fisheries, which show large variability depending on fishery, and the used median is therefore likely to be an inaccurate representation of the Estonian fishery. Dredge fisheries span from low fuel use fisheries (e.g. Danish blue mussels at <50 l diesel/ton liveweight) to very fuel intensive fisheries (e.g. scallops at

>1000 l diesel/ton liveweight) (FEUD 2024) and where on this scale the Furcellaria fishing falls needs to be determined by future studies.

Currently, the majority of the seaweed used for furcellaran extract production is not supplied from dredge fisheries but rather from beachcast seaweed collected by local residents. This was excluded from the analysis in this study as there is a lack of data. The available information also suggests a wide range of transport distances, transport modes, collection yields and drying methods, making assumptions challenging.

Currently the use of seaweed on Saarema follows a very linear, single product approach and the processing operations focus only the extraction of furcellaran. Seaweeds have been shown to contain a multitude of different substances like the extracted furcellaran, but also proteins, pigments and polysaccharides. Many of these substances have interesting traits making them relevant for applications in the foods and cosmetic industry but also medical applications due to e.g. anti-inflammatory or anti-diabetic effects (Kulikowski et al. 2021). Apart from extracts, the seaweed biomass has possible applications such as fertilizers (current use case), biodegradable packaging or as biogas feedstock. Multi-output seaweed biorefinery systems have been found to potentially improve sustainability and circularity compared to single product focused production. By increasing both added value and produced products from the biomass, environmental impacts can be shared by more products, lowering the impact of each individual output. These systems come however with increased complexity and dependency between the different production steps which requires more complex technical solutions and improvements still to be made (Ekman et al. 2022, Zhang et al. 2024).

Greenland

The fishery and processing operations studied in the Greenland case study highlight the carbon footprint hotspots within the system, mainly stemming from direct or indirect use of fossil-based energy sources for fishing vessels or electricity and heat generation. The main contribution to the carbon footprint of the final product was the fuel use of the well boat. Improvement actions in this area are limited, as the wellboat is crucial to the secure and adequate transport if the live fish. One feasible change leading to potentially lower carbon footprint is energy optimization during operations, hybrid-solutions using e.g., batteries to optimize diesel use, or use of alternative fuels with lower GHG emissions like e.g. methanol. Much can often be done in terms of energy saving, which goes hand-in-hand with economy, but switching to alternative fuels may be limited by the initial investment costs needed and other technological challenges, including available infrastructure on land (Ziegler and Hornborg 2023).

Large potential for reducing emissions post-harvest is improved resource utilisation by increasing by-product use in other applications. When processing cod to fillet or J-cut (fish without guts or head) products, side streams such as cod liver and intestines, bones, heads or filet trimmings and bellyflaps are produced. Possible use cases for these are processing into e.g. omega 3/6 rich liver oil as dietary supplements, proteins and enzymes, culinary uses (fish head soup), extraction of collagen from bones and cartilage for cosmetic applications or less complex processing into feed ingredients (fishmeal) Ghaly et al. 2013). There are multiple hinders limiting the byproduct use to current levels and leading to a majority of byproducts being flushed out to sea again. One limiting factor on Greenland is economic sustainability, as increased byproduct utilisation also means increased workload for the needed processing and packaging steps as well as shipping required for uses that can't be realised within the current processing facility. Since byproducts tend to be of lower economic value, the additional cost often can't be regained. With Greenland being more remote compared to other regions with larger fish processing sectors, like e.g. Norway, especially the higher shipping cost to market leads to byproducts would probably be less competitive on the global market. Another factor limiting the use of byproduct is the availability of manpower. Since the processing of this cod product is located in a remote location, limited workforce is available and therefore the available work capacity is naturally concentrated on products of higher value (person et al. 2023).

When comparing the carbon footprint of the Greenlandic cod filets to Norwegian cod filets that are available on the European market, they have a higher carbon footprint, both when compared at landing and as finished product at retail. The main reason for the lower emissions of the Norwegian filets is lower fuel use in fishing operations and significantly higher byproduct utilisation between 40-70% (Winther et al. 2020).

This study demonstrates however a weakness of LCA, which is the non-ability to quantify product quality. The Greenlandic cod filets production system is optimised after ensuring the shortest possible processing time from live fish to cod filet by keeping the fish alive as long as possible before slaughter and keeping the time from slaughter to freezing to under two hours. Comparatively, the dominating volume of Norwegian cod filets are likely sourced from trawled or gill net fished cod, which can have longer times and transport distances between catch, processing and freezing of the final product (Winther et al. 2020) – but there are other opportunities to safeguard product quality through e.g. processing onboard vessels. LCA outputs are predominately measured in physically measurable qualities like product weight or protein content. The aspect of filet freshness and quality could not be quantified in this assessment but could lead to different results.

Italy

In the Italian case study, the traditional use of tuna byproducts in a more industrial setting was investigated by assessing the carbon footprint of co-production of canned tuna loins and bottarga based on roe in Sicily. Byproducts arise at multiple steps in the production chain, at the pre-processing close to the landing harbours and later processing in Sicily. This geographic spread complicates coordinated increased use of byproducts as different actors and regional conditions have to be considered. For both products, GHG emissions were driven by fuel use during fishing and energy use during processing –

combined contributing to over half of the emissions at processing plant gate. Despite long transport distances for the pre-processed tuna from the different fishery locations to Sicily, the impact of transport is comparatively minor for both products due to efficient transport via cargo vessels.

Greenhouse gas emissions associated with processing are driven by energy use, both electricity and natural gas. The fossil free portion of Sicilian electricity production from wind and solar energy has been at 39% in 2023, with historical values ranging from 31-39% in the last 5 years. The remaining 61% are mostly generated using natural gas and oil (Electricity maps 2024). Opportunities for reducing GHG emissions comprise of energy saving strategies through process optimisation and/or own green energy production through e.g. use of rooftop solar panels, as well as reducing the need for natural gas in processing.

The proportional impact on the GHG emissions from packaging of the two products is noticeably different, where the glass jar used for bottarga have a considerably larger contribution than the metal cans used for the canned loins (25% vs. 9% of total carbon footprint). This is due to bottarga being packaged in small amounts (<50g/package) and is thus associated with relatively large weights of glass jar per product volume. Alternative packaging using other materials (e.g. coated paper or recycled plastic containers) would likely lower the carbon footprint. However, less “luxurious product appearance” may conflict the premium, delicacy status of bottarga as other packaging might not match consumer expectations and willingness to pay. Canned loin packaging has a lower GWP, but emission reduction potentials can also be found here. Poovarodom and colleagues (2012) investigated different tuna packaging options and found that retort pouch or retort cup packaging (made from plastic and metal film) are associated with less than half of the carbon footprint than a comparable metal can packaging.

The carbon footprint of canned tuna is subject to a handful of previous studies, but due to different fishing methods, year, region of origin and processing and LCA method choices vary making a direct comparison with the results from this study impossible. A comparatively wide range of GWP per 1 kg of packaged canned loins could be found, ranging from about 3 to 12 kg CO_2 eq. (Avadi et al. 2015, Carbon Cloud 2024, De Vlieghere 2023, AGRYBALYSE 3.1.1). Bottarga has not been evaluated by LCA before, so no comparison to literature values can be made.

The production of canned tuna loins and bottarga was also used to investigate the consequences of central LCA method decisions when assessing environmental impacts of products – co-product allocation. It could be demonstrated that choice of allocation method was central in this assessment, with major influence on results. This particularly applies for the co-product bottarga, as the relative difference in volume of the utilised tuna trimmings (which includes the tuna roe) compared to loins is substantially different than the proportion between tuna trimmings value and tuna loins value.

Allocating environmental burdens between co-products is a common problem faced in LCAs of food production systems, leading to different standards and recommendations that vary depending on product sector, applied standard or even country/region of the LCA practitioner. This presents a challenge with LCA in general and a potential hinder for current and future, LCA-based, sustainability work for companies. This is because it complicates the comparison of studies and product groups as choice of allocation method affects results which calls for transparency to not risk greenwashing. By reporting results using different allocation methods and/or providing the allocation data for recalculation by other users, these hinders can better be addressed and thereby improve future studies and communication of results.

Conclusion

This study mapped greenhouse gas emissions of three different production systems that are based on marine resources to produce foods and biomaterial to evaluate the potential implications related to byproduct utilisation. Conclusive for all three case studies was that the primary production (fishing) of the raw material was the step in the value chain that contributed the most to the carbon footprint of the final products in the current production system. Therefore, increased utilization of the whole volume produced is key for progressing towards more sustainable production systems, i.e. allow for more output out of less input. LCA-based assessments of co-products may however be challenging due to the strong influence of methodological decisions on allocation of environmental burdens, calling for improved transparency for best practice. Furthermore, increased byproduct utilisation does not only lower carbon footprints of the main products but may also offer increased revenue – but only if optimized processing throughout the value chain can be achieved.

7 Appendix I – Greenland case study

The analyses of the Atlantic cod fishery and processing in Greenland was based on data provided by a seafood company managing the entire value chain of the analysed production system. Due to the sensitive nature of the datapoints, these were not included in the public version of the project report.

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8 Appendix II – Estonia case study

In this appendix, all data used in the Estonia case study is documented.

8.1 Seaweed farming

Farming of different seaweed species is an emerging sector in western countries, whereas large scale production has been ongoing for centuries in Asia. Farming of red seaweeds using long line culture (Seaweed plants attached to ropes suspended in the water column) is an established technique, but no farming of furcellaria species is currently done based on the authors knowledge. In this study, data from an LCA study focussing on the farming of the red seaweed *Gracilaria chilensis* is used to represent the theoretical production of furcellaria of the Estonia coast (Aitken et al. 2014, Table A2.1). As the fuel use data in Aitken et al. was deemed too low for European seaweed farming systems, an adjusted number was used based on the average fuel use per ton fresh weight from three commercial or pilot scale seaweed farming operations (Nilsson et al. 2022, Taelman et al. 2015, Thomas et al. 2021, Table A2.1).

Table A2.1: Material and energy inputs per ton fresh weight seaweed produced from longline culture.

Material	Amount	Unit
Rope (Nylon)	2.0	kg
Anchor (concrete)	14.4	kg
Steel	0.6	kg
Buoys (PE)	0.8	kg
Aluminium	<0.1	kg
Diesel	28.1	l
Electricity	0.3	kWh

8.2 Seaweed fishery

In the literature, there is only very limited data on dredged seaweeds published and the few available datapoints don’t cover key metrics needed for LCA modelling like fuel use per ton harvest etc. A simplified modelling approach for dredged furcellaria seaweed in Estonia was therefore chosen and purely based on fuel use metrics from comparable fisheries. Infrastructure use of boat and dredging equipment not considered as it has been shown to be of low importance for carbon footprint assessments of fisheries in previous studies (Winter et al. 2020)

Fuel use data from the fisheries energy use database (FEUD) was used as a proxyfor the Estonian fishery. In the database, 61 individual fuel use datapoints were available for dredged seafoods, predominately for bivalves or crustaceans but none for seaweed

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species. A median of all 61 datapoints was used, which set the theoretical fuel use per kg fresh, dredged seaweed at 381l diesel (FEUD 2024).

Drying

After landing, the dredged (and in this study also the farmed) seaweed is airdried by loosely distributing it on a field close to the landing harbour. Here the water content of the biomass is reduced from ca. 85% to 20% before the biomass is transported to the factory for further processing.

Transport

The transport distance between the landing harbour and the furcellaran factory on Saareema is about 60 km by road. In this study, the assumption is made that 30% of this transport distance is done by tractor and trailer (accounting for transport to the drying location) and the remaining 70% by truck.

Furcellaran production

No technical data on the processing of the red seaweed furcellaria to furcellaran could be found in the literature. The extraction process of furcellaran is however similar to agar agar extraction, and technical processing data from Zhang et al. (2024) was used as a proxy (Table A2.2). Additionally, the yield from airdried seaweed to dried furcellaran was adjusted to better represent a furcellaria specific yield of 29% (Turvikene et al. 2005).

Table A2.2: Processing inputs per kg dried furcellaran produced.

Material	Amount	Unit	Comment
Seaweed (airdried)	3.46	kg	
Sulfuric acid	0.01	kg	
Sodium hydroxide	0.39	kg	
Sodium hypochlorite	0.02	kg	
Expandet perlite	0.01	kg	
Water	48.28	l	
Electricity	0.22	kWh	
Heat	2.41	kCal	Assumed to be heat from natural gas
Wastewater treatment	48.28	l	

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9 Appendix III – Italy case study

In this appendix, important data points and assumptions are documented. Technical primary data from the processing step was not included following the wishes of the tuna processing company participating in the study.

9.1 Fisheries

The tuna species predominately processed in the canning facility is yellowfin tuna (*Thunnus albacares*) sourced from purse seine fisheries in the central Pacific, eastern central Atlantic and southeast Pacific (FAO fishing areas 34, 71, 77, 87).

Tuna roe for bottarga production is mostly sourced from internal processing of yellowfin tuna but additional roe from bluefin tuna (*Thunnus thynnus*) caught with purse seine is also used.

In the modelling, the process "Yellowfin Tuna, ECA, Seine, average, at landing/CI U" from the AGRYBALYSE database (Version 1.4 2020) is used to represent both yellowfin and bluefin tuna.

9.2 Transports

The tuna used for both the canned tuna products and bottarga is shipped from their respective landing harbours to Sicily. For this transport aboard a container ship with refrigerated containers is assumed. Transport distances were calculated using the website seadistance.org. Furthermore, a refrigerated truck transport in both the country of origin and on Sicily is assumed. Table A3.1 summarises the transport distances relevant in this study.

Table A3.1: Transport distances of tuna loins, rounds and quarters used in tuna canning and bottarga production.

Transport mode	**From**	**To**	**Distance (nm)**	**Distance (km)**
Container (refrigerated)	Ecuador	Italy (Trapani)	6075	11251
Container (refrigerated)	Madagaskar	Italy (Trapani)	4400	8149
Container (refrigerated)	Taiwan	Italy (Trapani)	7700	14260
Container (refrigerated)	Solomon Islands	Italy (Trapani)	9100	16853
Truck (refrigerated)	Harbour to processing			50

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9.3 Pre-processing

The tuna used for canning and bottarga in Sicily, arrives pre-processed at the canning factory. The raw material arrives in three product forms: cooked loins, round tuna (raw, whole tuna without head and fins) and quartered tuna (raw, no head, fins or guts). Bellow, the conversion factor from fresh tuna to the different product forms is described in table A3.2.

Table A3.2 Conversion factors from liveweight tuna to the different product forms applicable in this study.

Cut	share of liveweight tuna (%)	Comment	Source
Loins	42.5		FAO (2000)
Round	69.9		FAO (2000)
Quartered	69.9	No literature available, assumed to be the same as round	

9.4 Allocation

One central method decision within LCA studies is the division environmental burden for processes that yield multiple products. While best avoided, it is in practise often necessary to include in the modelling because of the available data or study hypothesis. The division of burden between coproducts can be based on different parameters, biophysical being the ones suggested in the relevant ISO standards (ISO 2006a,b) followed by economic value. In this study we applied mass-based allocation as the primary allocation method but have, as a sensitivity analysis, included results based on economic allocation. For byproducts from the pre-processing stage a utilisation rate in other applications of 15% is assumed. Table A3.3 summarises the different products values and share of total output mass used for the allocation calculations.

Table A3.3 Value of different tuna cuts and final products

Product	Value (€/kg)	Comment
Loins	6.0	
Round/Quartered	3.4	
Pre-processing byproducts (utilised)	0.1	Assumed value, 15% utilisation rate assumed
Canned tuna loins	14.0	
Bottarga	72.4	

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