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Ayla Frost
School for International Training, ayla.frost@mail.sit.edu

Joana Almeida
NOVA School of Science and Technology, CENSE - Department of Environmental Sciences and Engineering, js.almeida@fct.unl.pt

Joana Dionisio
School for International Training, joana.dionisio@sit.edu

Radu Godina
NOVA School of Science and Technology, UNIDEMI- Department of Mechanical and Industrial Engineering; Laboratório Associado de Sistemas, r.godina@fct.unl.pt

Cátia Magro
School for International Training, catia.magro@sit.edu

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Environmental Analysis of Codfish Production and Consumption in Portugal

Ayla Frost[1], Joana Almeida[2*], Joana Dionísio[1], Radu Godina,[3,4] and Cátia Magro[1*]

[1]School for International Training

[2]NOVA School of Science and Technology, CENSE – Department of Environmental Sciences and Engineering

[3]NOVA School of Science and Technology, UNIDEMI- Department of Mechanical and Industrial Engineering

[4]Laboratório Associado de Sistemas Inteligentes

***Correspondence: js.almeida@fct.unl.pt, catia.magro@sit.edu**

Abstract

Codfish, a typical dish consumed frequently in Portugal, is fished in the cold Northern Atlantic waters far from the Portuguese coast. Thus, regional tensions and the environmental impacts of Portuguese codfish importation and production are significant current issues. The present study uses a life cycle assessment methodology to evaluate the array of environmental impacts of the production of 1 kg of codfish, following a cradle to gate approach. The life cycle inventory was grouped into catch and preprocessing, transit, and curing stages. The data collection of products and processes in each stage was based on scientific peer reviewed documents, technical reports, and the Ecoinvent database. The ReCiPe 2016 method, both midpoint and endpoint, was applied to determine the impacts of codfish production using SimaPro software. Results show that the curing stage of production is responsible for most environmental impacts (90-99%), followed by the capturing stage (25-45%). Thus, improving factory efficiency and adjusting fishing techniques are key factors to increase the sustainability of the codfish life cycle.

Resumen

El bacalao, un plato típico consumido muy frecuentemente en Portugal, se pesca en las frías aguas del Atlántico norte, lejos de la costa de ese país. Por lo tanto, las tensiones regionales y los impactos ambientales de la importación y producción portuguesa de bacalao son problemas significativos en la actualidad. El presente estudio tiene como objetivo presentar una metodología de evaluación del ciclo de vida para evaluar una serie de impactos ambientales en la producción de 1 kg de bacalao, desde su origen hasta la mesa del consumidor. El inventario del ciclo de vida se agrupó en las etapas de captura y preprocesamiento, tránsito y curación. La recopilación de datos de productos y procesos de cada etapa se basó en documentos científicos revisados por pares, informes técnicos y la base de datos de Ecoinvent. Se aplicó el método ReCiPe 2016, tanto de punto medio como de punto final, para determinar los impactos de la producción de bacalao, a través del uso del software SimaPro. Los resultados muestran que la etapa de curación de la producción es responsable de la mayoría de los impactos ambientales (90-99%), seguida de la etapa de captura (25-45%). Por lo tanto, mejorar la eficiencia de las fábricas y ajustar las técnicas de pesca son factores clave para aumentar la sostenibilidad del ciclo de vida del bacalao.

Keywords

Life cycle assessment, sustainability, environmental impact, codfish

Introduction

The continuous growth of the world's population has fueled ongoing research into developing more sustainable pathways to food production (Rodrigues et al., 2021). In parallel, energy consumption has increased as a result of better living standards and a shortage of arable lands, as well as a growing population (Taherzadeh-Shalmaei et al., 2021). The demand for fish in Europe is substantial, with various species contributing to diets across the continent. In the EU-27, the household expenditure on fish and seafood grew by 7% since 2020. The estimated EU apparent consumption of fish accounted for 10.41 million t of live weight equivalent, meaning 23.28 kg per year per person. Portugal stands out as the major EU consumer of fishery and aquaculture products (European Commission Directorate-General for Maritime Affairs and Fisheries, 2022).

In Portugal, codfish consumption has become deeply rooted in culinary traditions and cultural practices. While historical codfish imports came mainly from Canadian regions, most Portuguese cod imports originate from Norway (49%), followed by Denmark (27%) and Iceland (19%) (Madsen & Chkoniya, 2019). Notably, Norway plays a major role in the global codfish trade, capturing approximately one-third of the annual global catch of Atlantic cod, amounting to around 326,989 t in 2020 (European Market Observatory for Fisheries and Aquaculture Products, 2018; Food and Agriculture Organization of the United Nations, 2020). Around 66% of the dried and salted cod processed in Norway is imported to Portugal (European Commission, 2018). Although Portugal is the primary destination for Norwegian freights, these exports account for only 36% of the dried and salted cod consumed in Portugal (European Commission, 2018). Approximately 64% of dried and salted cod in Portugal is processed locally from frozen cod and semi-processed cod imports (European Commission, 2018). Portugal, along with Greenland, leads in annual fish consumption, with codfish representing around 40% of this total (Oliveira et al., 2016). In fact, a survey conducted in 2013 on Portuguese seafood preferences revealed that 62.6% of respondents consumed codfish at least once a week (Cardoso et al., 2013). Given the substantial scale of codfish consumption in Portugal, it becomes crucial to consider its environmental impacts, particularly considering the presumed environmental toll of transporting the fish from Northern European countries to Portugal.

In the study of food and food systems, the life cycle assessment (LCA) tool is frequently employed to evaluate environmental impacts over the entire lifespan of a product. This standardized framework, in accordance with ISO (International Organization for Standardization) standards, encompasses four major steps: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation (ISO, 2006a, 2006b). A LCA conducted by Parker and Tyedmers (2015) found that most life cycle greenhouse gas emissions in the fishing industry stem from the fuel used by fishing vessels, suggesting that fuel consumption can serve as an effective indicator of the carbon footprint of unprocessed fish. Cooling agent leakage also emerged as a significant contributor to greenhouse gas emissions, accounting for approximately 13% of total fishery emissions (Iribarren et al., 2011). These studies indicate that the capture and transportation of codfish might result in greenhouse gas emissions that contribute to climate change (Parker & Tyedmers, 2015). Previous LCAs have also focused on the fishing and production stages of codfish. One assessment revealed that the fishing phase of codfish production accounted for the most significant environmental impact, particularly noting the substantial but inadequately explored effects of trawling on the seafloor (Ellingsen & Aanondsen, 2006). Another study echoed these findings, identifying fuel consumption and refrigerant leakage during the fishing stage as the primary sources of environmental impact (Svanes et al., 2011). A separate assessment highlighted the potential ecosystem threat posed using copper as a biocide applied to the hulls of fishing vessels due to its ecotoxicity (Ziegler et al., 2003). Although these previous studies have conducted LCA of codfish from fishery to table, they have not specifically focused on the life cycle of codfish in Portugal, integrating the cultural significance of codfish with its environmental impact. The present study aims to fill this research gap by integrating codfish as a cultural phenomenon in Portugal with the environmental effects of its production and consumption, quantified through an LCA methodology. Therefore, the objectives of the study are to: (1) determine the environmental impacts of codfish production; (2) identify critical processes in its production; and (3) provide recommendations for improving the sustainability of the codfish life cycle.

Methods

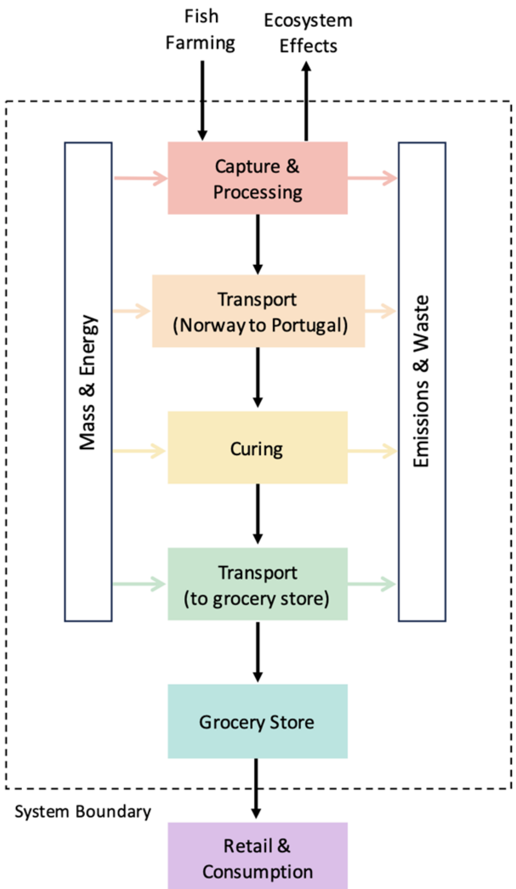
LIFE CYCLE ASSESSMENT

Goal and Scope Definition

To analyze the environmental effects of codfish production, this study employs a LCA methodology, based on ISO 14040 (ISO, 2006a) and ISO 14044+A1 (ISO, 2006b). The main goal of the present work is to assess environmental impacts from the codfish capture until its arrival to the grocery store, as well as to identify critical processes and provide improvement actions. Thus, the scope of this study is a “cradle to gate” approach, one that traces the journey of codfish from sea capture to the market.

The functional unit defined for this study is 1 kg of codfish, being in line with other studies that addressed the impacts of cod (Eliassen et al., 2021; Smárason et al., 2014). Codfish is traced from its capture, to transport, to curing, and to transit, and ultimately to the grocery store. Due to its low presence in the system evaluated here, cod farming, a technique used for capturing cod, is excluded (Standal & Bouwer Utne, 2007). Capital goods, retail, consumption, and waste production and ecosystem effects from trawling and other fishing techniques, as well as changes in technology or practices over time, are also not considered in this study. Figure 1 presents the flowchart of the system analyzed.

Figure 1: System Boundaries of Codfish Production and Consumption



System Description and Data Collection

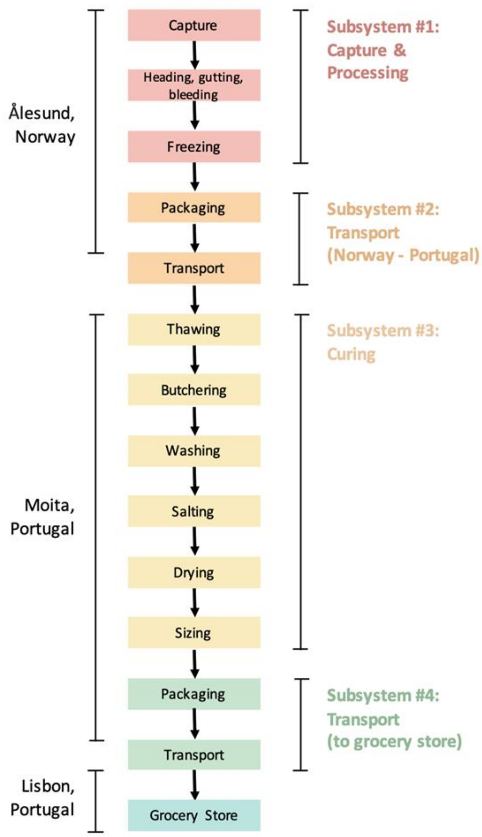
Codfish production can follow several pathways. In Portugal, most imports come from Norway, Denmark, and Iceland (Madsen & Chkoniya, 2019). As Norway is responsible for the largest proportion of imports, this study focuses on codfish production from its capture in Norway to its retail in Portugal. Approximately 31% of Norwegian cod is caught using gillnets, 29% bottom trawling, 17% Danish seine, 13% uses other coastal fishing methods, and 9% applies long line techniques (Ziegler et al., 2013).

When the fish arrive onshore, it can be transported to a Norwegian processing facility for pickling, wet salting, or dry salting. Codfish can also be transported directly to Portuguese factories for Portuguese processing techniques. The present study focuses on codfish in the context of Portuguese culture and tradition, tracing the codfish that is directly transported to Portugal in a frozen state. More specifically, this LCA is specific to the processing that frozen cod undergoes at a specific site. In this case, the study is narrowed to Riberalves. Riberalves is one of the largest cod processing companies, processing over 30,000 t of codfish a year, approximately 8% to 10% of codfish that is caught per year (Riberalves, 2023).

To determine shipping distances, this study zooms in on a processing facility in Norway, a processing facility in Portugal, and a grocery store in Lisbon as a sample route that codfish can take (Annex I, supplementary data). The major cod processing companies are typically located near Ålesund, Norway (European Market Observatory for Fisheries and Aquaculture Products, 2018a). A company called Lerøy Havfisk AS (Ålesund, Norway) was identified as a sample starting point for the journey of the frozen cod.

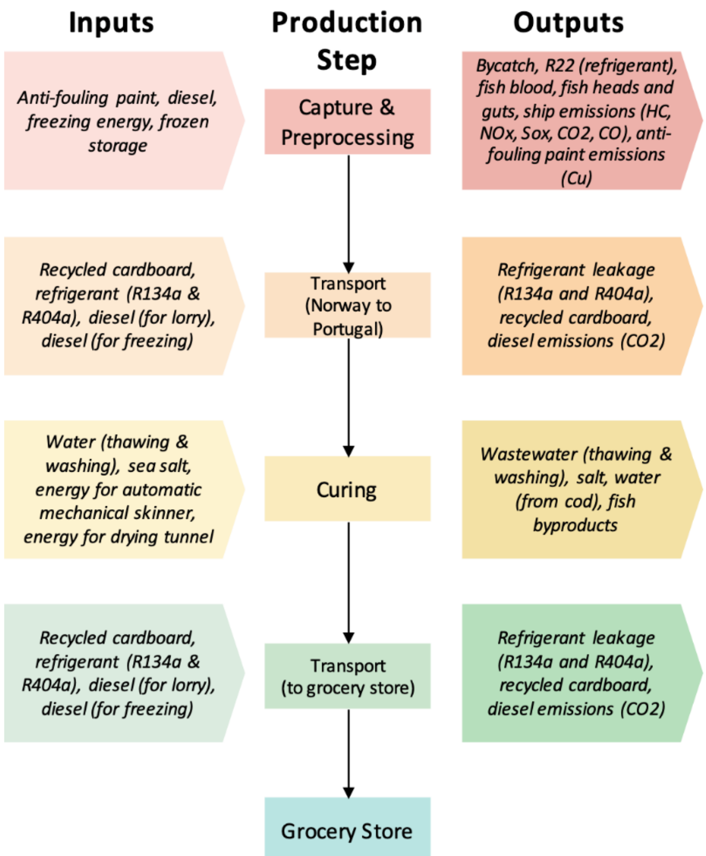
Lerøy Havfisk AS is a Norwegian fishing and processing company, with the largest trawling fleet in Norway (10 fishing vessels and 29.6 cod trawling licenses) (Lerøy Havfisk, 2023). An industrial unit in Portugal, owned by Riberalves, was identified as a sample processing site. The factory in Moita is the largest codfish factory in the world (Associação de Produtores de Espécies Demersais dos Açores, 2015). This study will use a local store, Pingo Doce Tomás Ribeiro as a sample retail site. Land transport distances between the locations were calculated using Google Maps. Data were collected from other LCAs, government data, peer-reviewed articles, and graduate theses and dissertations. The flow chart of the journey undertaken by codfish, from its capture to the moment it arrives in the grocery store is displayed in the flowchart (Figure 2).

Figure 2: Flowchart with Codfish Production Route



The codfish life cycle is broken into four subsystems (Figure 3): (1) Capture and pre-processing; (2) Transport: Norway to Portugal; (3) Curing; and (4) Transport: processing facility to grocery store.

Figure 3: Codfish Production Subsystems with Inputs and Outputs



Life Cycle Inventory

CATCH AND PREPROCESSING

The first subsystem of codfish processing is capture and pre-processing. Codfish is typically captured aboard a vessel in the Norwegian Sea, Spitzberg, Bear Island, or the Barents Sea (Pascoal, 2023). Some of the major environmental effects of the capture phase stem from diesel emissions from the ship. A study of Norwegian fishing fleets estimated Norwegian cod fishing fleets to consume an average of 0.24L of diesel per kg of landed cod (Ziegler et al., 2013b). Emissions from this diesel combustion were estimated from a LCA based on Swedish cod fisheries in the Baltic, which broke down emissions of HC, NOx, SOx, CO_2, and CO from Swedish cod fishing (Ziegler et al., 2003) (Table 1).

Anti-fouling paint is another environmental threat associated with industrial fishing. Anti-fouling paints are applied to a ship's hull to prevent marine life from attaching to the body of the boat. Historically, a hazardous chemical based on tributyltin (TBT) was used for this, but copper has come to replace TBT as a less-toxic alternative (Carić et al., 2016). Although copper is less hazardous, it has been shown to influence ecosystems by inhibiting biological and reproductive processes (Guardiola et al., 2012). Data on anti-fouling paint usage and emissions was ascertained from a study of Swedish cod fisheries, which estimated that approximately 0.5 ml of anti-fouling paint is used per kg of landed cod through a study of 30 Swedish fishermen (Ziegler et al., 2003). It was estimated that 0.02 g of copper, which is one of the most dangerous components of anti-fouling paint, was emitted per 200 g of cod, which translates to 0.1g of copper emitted per functional unit (FU) (Ellingsen & Aanondsen, 2006).

Bycatch is another type of waste associated with fishing practices, which refers to the unintended capture of non-target marine animals. Rates of bycatch depend heavily on the fishing technique, with trawling producing significantly less bycatch than Danish seine fishing (Alverson et al., 1994). A study of Swedish cod fisheries estimated that on average, 1.5% of the codfish haul is bycatch (Ziegler et al., 2003) (Table 1).

Table 1: Inventory List of Codfish Catch and Preprocessing

Input/Output	Quantity (per FU)	Stage	References
Input: Material			
Anti-fouling paint	0.5 ml	Capture	(Ziegler et al., 2003)
Input: Energy			
Diesel (for shipping vessel)	0.24 L	Capture	(Ziegler et al., 2013)
Freezing energy	0.133 kWh	Freezing	(Ziegler et al., 2013)
Frozen storage	234 KJ	Freezing	(Ziegler et al., 2013)
Output: Material			
Bycatch	0.015 kg	Capture	(Ziegler et al., 2003)
R22 (refrigerant)	0.224 g	Freezing	(Ziegler et al., 2013)
Fish blood	0.59–1.89 kg	Heading, Gutting, Bleeding	(EU IUU Fishing Coalition, 2021)
Fish head and guts	0.4083 kg	Heading, Gutting, Bleeding	(Association of the United Food and Agriculture Nations, 2022)
Output: Emissions			
Ship Emissions (HC)	1.92 g	Capture	(Ziegler et al., 2003)
Ship Emissions (NO_x)	55 g	Capture	(Ziegler et al., 2003)
Ship Emissions (SO_x)	3.11g	Capture	(Ziegler et al., 2003)
Ship Emissions (CO_2)	0.53 g	Capture	(Ziegler et al., 2003)
Ship Emissions (CO)	2433 g	Capture	(Ziegler et al., 2003)
Anti-fouling paint emissions (Cu)	0.1 g	Capture	(Ellingsen & Aanondsen, 2006)

After the fish are captured, they are typically beheaded, bled, and gutted aboard the ship (Oliveira et al., 2016). Weight estimations for the mass of fish heads, blood, and guts were estimated using official conversion ratios to calculate the mass of the live catch from the mass of the beheaded and gutted landed fish (Association of the United Food and Agriculture Nations, 2022; EU IUU Fishing Coalition, 2021). After the fish are beheaded, they are chilled or frozen aboard the vessel. Typically, the cod is frozen into blocks of 25 kg and stored at approximately -30°C onboard the vessel (Aas et al., 2010). A variety of refrigerants are used to keep the product cool. The most used refrigerants on Norwegian fishing vessels are R22, ammonia, and CO_2. Of these three refrigerants, R22 is the chemical with the most significant global warming potential and ozone depletion potential (Ziegler et al., 2013). Although R22 is being phased out of newer vessels, as of 2016, 70% of the global fishing fleet still uses R22 as their primary refrigerant (Semaev, 2021).

Within the Norwegian fleet of demersal fishing vessels, it has been estimated that 0.224 g of R22 are emitted per kg of cod that is caught. To estimate the energy that is used to chill and freeze fish aboard fishing vessels, the same study estimated that an average of 133 Kwh of energy are consumed per t of frozen fish, which translates to 0.133 Kwh per kg. Processing companies store frozen fish for approximately 90 days before transport (Ziegler et al., 2013). Taking into account that frozen storage is estimated to consume 2.6 KJ/kg*day, fish freezing is estimated to consume 234 KJ per kg of cod (Thrane, 2004).

TRANSIT

Frozen cod is typically transported from Norway to Portugal in a 40 ft lorry, which contains approximately 22.5 t of cod. The most popular trucks for transport are a Volvo FH and Scania R500 (Ziegler et al., 2013). To calculate inputs and outputs associated per FU of cod, inputs and outputs were first estimated per journey, then divided by 22,500 kg of cod per journey to estimate the FU. The distance from the fishery Lerøy Havfisk AS to the industrial unit in Moita by road is approximately 4000 km. Though Google Maps estimates the journey to take 42 h, a Norwegian study found that transportation by road typically takes approximately 5-6 days overall (European Market Observatory for Fisheries and Aquaculture Products, 2018).

A study of Norwegian cod production estimated diesel consumption for refrigeration to be around 0.32 L/km on flat European terrain (Ziegler et al., 2013). For a 4000 km journey, this translates to approximately 1280 L consumed per journey. Diesel engines produce 2.7 kg of CO_2 per liter of diesel fuel (Natural Resources Canada, 2014). If one journey consumes approximately 1364-1448 L to complete, one journey emits 3682 to 3909 kg of CO_2 (Table 2).

The energy used to freeze the cod during transport is derived from the diesel fuel used to power the lorry. Diesel consumption for refrigeration is approximately 2-4 L/h, depending on the load and distance. This means 84-168 L of diesel are consumed by the cooling system for a 42h journey. Trucks also use refrigerants to keep products cool. The main refrigerants used in Norwegian lorries are R134a and R404a. Approximately 6.5 kg of refrigerant is used per truck, 5-10% (or 0.325 kg to 0.65kg) of which is estimated to leak over the course of the journey. Frozen fish are typically transported in cardboard boxes, with approximately 25 kg of fish in each box. Since one cardboard box weighs approximately 2.0kg, 0.1kg is used per one kg of frozen cod (Ziegler et al., 2013).

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For the final stage of the journey, the dried and salted codfish is transported from the processing facility to the grocery store, where it is resold to consumers. The product is transported to a variety of locations, but this study focuses on Pingo Doce Tomás Ribeiro as a sample retail location in Lisbon. The journey from the industrial unit in Moita to Pingo Doce Tomás Ribeiro in Lisbon is 43 minutes amounting to 43.2 km.

Information on refrigerants, diesel consumption, and diesel emissions for this subsystem were readjusted from the values ascertained in Subsystem #2 to the scale of the 43.2km journey. Codfish is generally sold in grocery stores without packaging. However, as with Subsystem #2, they are typically packaged in cardboard boxes for transport with approximately 25 kg of fish in each box (Ziegler et al., 2013).

Table 2: Inventory List of Codfish Transit

Input/Output	Quantity (per kg)	Quantity (per journey)	Stage	References
Input: Material				
Refrigerants: R134a and R404a	0.29 g	6.5 kg	Cooling	(Ziegler et al., 2013)
Recycled Cardboard	0.1 kg	n/a	Packaging	(Ziegler et al., 2013)
Input: Energy				
Diesel (Lorry)	0.06 L	1280 L	Transport	(Ziegler et al., 2013)
Diesel (Freezing)	0.004 L - 0.007 L	84 L -168 L	Freezing	(Ziegler et al., 2013)
Output: Material				
Refrigerant leakage: R134a and R404a	0.014 g - 0.028 g	0.325 kg - 0.65 kg	Freezing	(Ziegler et al., 2013)
Recycled Cardboard	0.1 kg	n/a	Packaging	(Ziegler et al., 2013)
Output: Emissions				
Diesel Emissions: CO_2	0.1636 kg – 0.1737 kg	3682 kg – 3909 kg	Transport	(Natural Resources Canada, 2014)

CURING

When the frozen fish arrives at the processing factory in Portugal, it needs to be dethawed. The fish are typically dethawed in a thawing tank of chilled running water for a period of 12-20 hours, depending on the size of the fish (Lorentzen et al., 2021). Due to a lack of data on cod processing specifically, this study uses an estimation based on generic fish processing of 10 t of water for every 25 t of fish, or 0.4kg water for every kg of cod (Business Bliss Consultants FZE, 2018) (Table 3).

After the fish is dethawed, it is butchered. The fish are scaled using an automatic mechanical skinner (Santos, 2017). An estimation from Norwegian whitefish processing plants estimates 661 kWh consumed per t of product in a mechanical skinner (Ziegler et al., 2013). After the fish is scaled, it is cut longitudinally down the center and the anterior two thirds of the vertebral column is removed (Piteira, 2017). Data on fish byproducts wasted during the butchering process was calculated using a UN document for converting product weight for fish to live weight (Association of the United Food and Agriculture Nations, 2022).

Table 3: Inventory List of Codfish Curing

Input/Output	Quantity	Stage	References
Input: Material			
Chilled Running Water	0.4 kg	Thawing	(Business Bliss Consultants FZE, 2018)
Water	1.52 kg	Washing	(Business Bliss Consultants FZE, 2018)
Sea Salt (1st Salting)	0.33 kg	Salting	(Oliveira et al., 2016)
Sea Salt (2nd Salting)	0.645 kg	Salting	(Associação de Produtores de Espécies Demersais dos Açores, 2015; Santos, 2017; Ziegler et al., 2013)
Input : Energy			
Automatic Mechanical Skinner	0.661 kWh	Butchering	(Ziegler et al., 2013)
Drying Tunnel	0.215 kWh	Drying	(Ziegler et al., 2013)
Output: Material			
Wastewater	0.4 kg	Thawing	(Business Bliss Consultants FZE, 2018)
Fish byproducts	0.28 kg	Butchering	(Association of the United Food and Agriculture Nations, 2022)
Wastewater	1.52 kg	Washing	(Business Bliss Consultants FZE, 2018)
Salt	0.78 kg	Salting + Drying	(Aas et al., 2010; Oliveira et al., 2016)
Water (from cod)	0.3 kg	Salting + Drying	(Oliveira et al., 2012)

After the fish is scaled, it must be washed to remove any remaining mucus and fish viscera. There are two primary washing processes: (1) the fish are placed onto a ramp which leads to a mat covered with a 20 cm layer of running water, under which the fish are immersed for a 10 second period; (2) the codfish passes through a tunnel filled with sprinklers for five seconds, then transitions onto a dry mat to remove some of the moisture (Piteira, 2017). One source estimates that the washing process requires 30 t of water for every 19.75 t of fish (Business Bliss Consultants FZE, 2018).

After being cleaned, the fish are typically salted in big vats, stacked in overlapping layers of fish and salt. During this primary salting step, approximately 0.33 kg of salt is used per FU (Oliveira et al., 2016). The cod is stored in these vats for 7 days, during which the fish are immersed in the brine formed by the salt and water released from the fish tissue. After this period of immersion, the fish are transferred to a pallet, where the brine is allowed to drain away continuously (Oliveira et al., 2016). This maturation period typically lasts approximately eight months at processing units. After this, the fish are washed for a second time (Piteira, 2017).

At this stage, the fish are referred to as green salted cod. Next, more salt is added, and the fish mature in refrigerated chambers at a temperature of 40ºC for about eight more months (Piteira, 2017). Different sources estimate different total amounts of fish throughout the entire process. A study of a Norwegian dry-salting technique estimates that approximately 1.5 kg of salt is used throughout the entire salting process (Ziegler et al., 2013). Another study estimates that approximately 0.4 - 0.45 kg of salt are used per kg of cod (Santos, 2017). A third source estimates that approximately 1 kg of salt is used per kg of fish (Associação de Produtores de Espécies Demersais dos Açores, 2015). To estimate the total amount of salt used in the life cycle inventory, these three values were averaged for an estimate of 0.975 kg of salt per kg of cod. The fish salting step uses approximately 0.33 kg of salt, meaning that the second salting step needs approximately 0.645 kg of salt per FU.

The machine used for drying is a York Systems evaporator, complete with an air circulation system, humidity sensors and heating and cooling system. Drying can last from 36 to 100 hours, between 18ºC and 24ºC (Piteira, 2017). A study of Norwegian processing of dried salted fish calculated energy estimates for drying technology. The study identified two main technologies that were used to dry the salted cod, one using 0.164 kWh per kg and one consuming 0.265 kWh per kg (Ziegler et al., 2013). For the purposes of this study, energy values were averaged to estimate drying energy per FU.

During this period, the salt content of the fish increases significantly while the water content decreases (Table 4). These values were used to calculate outputs of the salting and drying stages, including leftover salt and water leached from the fish. After the codfish is dried, the product is sized using industrial and automatic scales. The scales used are: Bilancial EV7-S and the Ruby RB60 (Piteira, 2017).

Table 4: Salt and Water Content of Codfish at Different Stages

Material	Fresh	Salted	Dried and Salted
Water content (%)	82[1]	60[2]	50[3]
Salt content (%)	0.2 – 0.5[2]	15 – 21[2]	14.6 - 20.4[3]

[1]*(Oliveira et al., 2012)* [2]*(Aas et al., 2010)* [3]*(Oliveira et al., 2016)*

MODELING

To scale the LCA to the scope of this time frame, this study uses SimaPro software to estimate the impacts of codfish processing. SimaPro is integrated with a database called Ecoinvent, which contains detailed information on energy and matter inputs and outputs for a variety of processes.

To estimate Subsystem 1, two processes related to the capture of hake (a fish closely related to cod) were selected and input into SimaPro. For this study, landed hake was used as a proxy for cod. Hake is in the same taxonomic order as cod, Merlucciidae, and like cod they are native to colder waters in the Atlantic and Pacific oceans (Murua, 2010). The first process is entitled "hake, capture by trawler and landing whole, fresh." This system describes the inputs and outputs associated with hake fishing using bottom trawling. The boundaries of this system include vessel construction, vessel maintenance, consumption of diesel and lubricants, and direct emissions to the water. Any processing after the ship reaches the port is excluded from this system. To supplement this process, a process entitled "hake, captured by long liner and landing whole, fresh" was also selected. This system describes the inputs and outputs associated with hake fishing using long lining. Although Norwegian cod-fishing fleets use other fishing techniques, including gillnets and Danish seine, bottom trawling and long-lines were the two fishing techniques that were available in the SimaPro software for hake. The two fish were weighted according to their relative use in Norwegian fishing fleets. Since bottom trawling is 3.22 times as prevalent as longline fishing, bottom trawling was estimated to represent about 76% of the mass of landed fish, while long-lining was estimated to represent approximately 24% of one FU of codfish (Table 5).

To represent Subsystem 2, two processes were selected: "market for transport, freight, lorry 16-32 metric t" and "operation, reefer, freezing, 40-foot, high-cube, R134a as refrigerant." The first process describes the inputs and outputs associated with transport in a lorry. Since fish are typically transported in a 22.5 t lorry, this transport was defined as a 16-32 metric t lorry. The units used in this process are t*km. To estimate this journey, one FU (which is 1/1000 t) is multiplied by 4000 km for a total of 4 t*km. The other process included in Subsystem 2 pertains to the freezing of a 40-foot reefer (refrigerated truck trailer). R134a was selected as a refrigerant over CO_2 because most Norwegian trucks have not transitioned to the more environmentally friendly CO_2-based refrigerants. The units for this process are kg*day. This 4000 km journey typically takes 5-6 days to complete. Thus, the amount was calculated based on an average 5.5-day journey for a value of 5.5 kg*day.

To estimate Subsystem 3, a process entitled "fish curing, small fish" was selected. Although cod is a larger species of fish, this process was selected because the processing steps closely resemble the processing steps that are outlined in the life cycle inventory section of this study, and no processes pertaining to large fish were available. This process includes infrastructure construction and maintenance, seafood processing, and direct emissions into the water. The processing step includes heading and gutting, washing/bleeding, salting, pressing, maturation, cleansing, centrifugation, fileting, packing, sealing, and storage.

To estimate Subsystem 4 a system entitled market for "transport, freight, lorry with refrigeration machine, cooling" was selected. At this stage in the life cycle, the cod does not need to be frozen but cooled, and less information is available about the types of trucks used to transport the codfish for this leg of the journey. Thus, a more generic system for lorry transport with a

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refrigeration unit was defined. The units for this process are metric t*km, so to transport 1/1000 t for 43.2 km, a value of 0.0432 metric t*km was input into SimaPro.

The ReCiPe 2016 method was used to determine the impacts of codfish production. The ReCiPe method is a LCA method that is well-accepted in the scientific community. It was developed in 2008, by RIVM, Radboud University Nijmegen, Leiden University, and PRé Sustainability, and updated in 2016 in collaboration with the Norwegian University of Science. The technique is used to transform the results of the life cycle inventory into a finite list of indicators. The scores for each of these indicators express the relative severity of the processes for each impact category.

Table 5: SimaPro Software Input Values (Ecoinvent 3 database)

Process	Amount	Unit	Calculations	Region
Hake, capture by long liner and landing whole, fresh	0.23684	kg	1kg * 0.09/(0.09 + 0.29)	Europe: Spain
Hake, capture by trawler and landing whole, fresh	0.76315	kg	1kg * 0.29/(0.09 + 0.29)	Europe: Spain
Market for transport, freight, lorry 16-32 metric ton, EURO3	4	t*km	1 t /1000 kg * 4000 km	Europe
Operation, reefer, freezing, 40-foot, high-cube, R134a as refrigerant	5.5	kg*day	1 kg * 5.5 days	Global
Fish curing, small fish	1	kg	n/a	Global
Market for transport, freight, lorry with refrigeration machine, cooling	0.0432	t*km	1 t /1000 kg * 43.2 km	Global

There are two types of indicators that can be calculated using the ReCiPe method: midpoint indicators and endpoint indicators. There are 18 midpoint indicators, which express specific environmental categories like climate change or freshwater eutrophication. There are three endpoint indicators, which are used to indicate the effect these midpoint categories have on three damage categories: 1) Human health; 2) Ecosystems; and 3) Resources Cost.

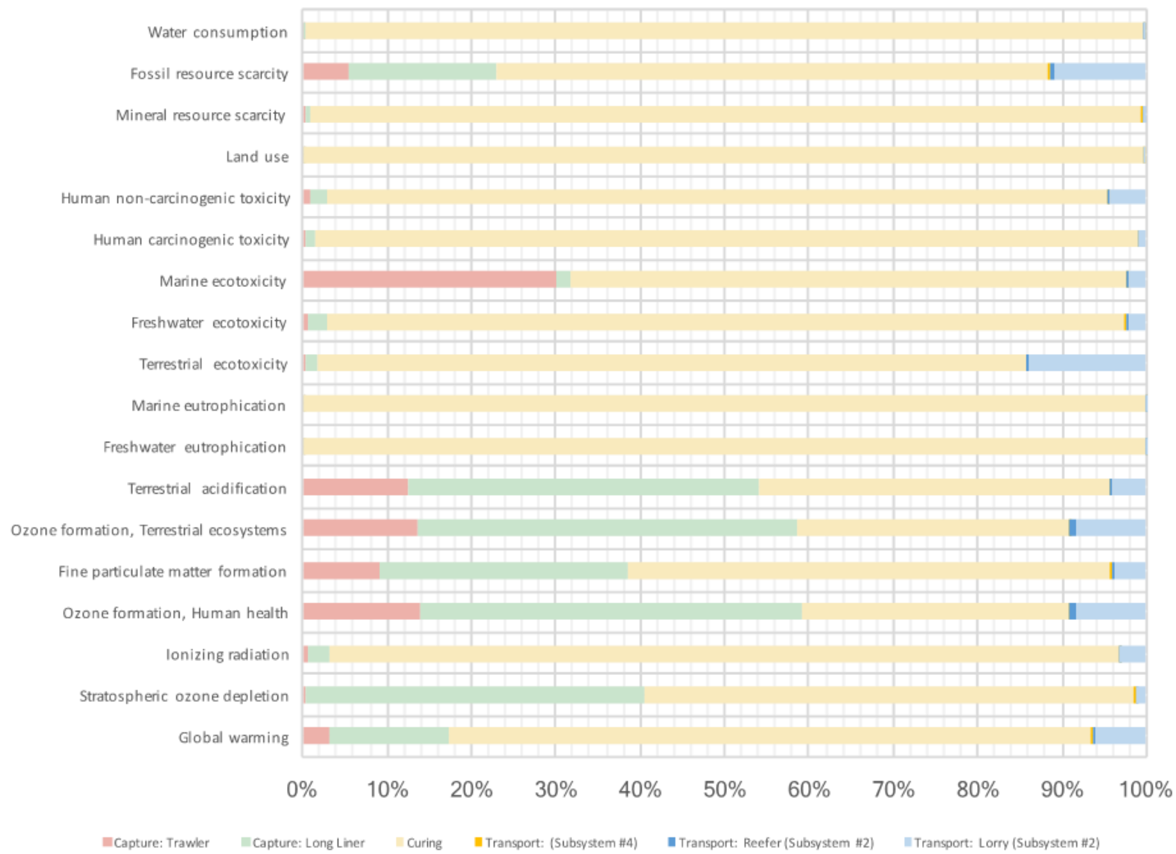
The ReCiPe 2016 framework displays the transformation of information from the primary data to the 18 midpoint impact categories and eventually to the three endpoint categories. Midpoint indicators are translated into the three endpoint indicators using damage pathways, like “increase in respiratory diseases” or “damage to freshwater species.”

Results and Discussion

IMPACT ASSESSMENT: ENVIRONMENTAL IMPACT CATEGORIES (MIDPOINT)

An analysis was conducted to evaluate the relative impact of each process involved in cod production on each of the 18 midpoint categories. Figure 4 displays the percentage impact of each of the six processes relative to the other processes involved.

Figure 4: Relative Environmental Impacts on Midpoint Damage Categories.



Curing was responsible for the greatest impact in most impact categories in comparison to the other processes involved in cod production. Curing was responsible for over 90% of impact in half of the categories, including ionizing radiation (93.65%), freshwater eutrophication (99.55%), marine eutrophication (99.68%), freshwater ecotoxicity (94.43%), human carcinogenic toxicity (97.46%), human non-carcinogenic toxicity (92.39%), land use (99.45 %), mineral resource scarcity (98.55%), and water consumption (99.08%). The curing process was responsible for over 99% of impact in the categories: freshwater eutrophication (producing 0.02 kg P eq), marine eutrophication (producing 0.00381kg N eq), land use (occupying 8.8 m2a crop eq), and water consumption (consuming 0.243 m^3).

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Capture using a long liner was responsible for the highest relative impact in two impact categories: ozone formation (human health) and ozone formation (terrestrial ecosystems). Capture using a long liner contributed to 45.28% of ozone formation regarding human health and 44.87% of ozone formation regarding terrestrial ecosystems relative to the other processes. This equates to 0.0253 kg NOx eq and 0.0254 kg NOx eq for human health and terrestrial ecosystems, respectively. Additionally, for the damage category of terrestrial acidification, capture by long liner and curing are within one percent of one another, suggesting capture via long liner was responsible for a significant portion of contributions to terrestrial acidification. In addition to the aforementioned impact categories, capture by long liner contributes to more than 25% of stratospheric ozone depletion and fine particulate matter formation.

Capture by trawler was responsible for the most significant proportion of damage for marine ecotoxicity, with values of approximately 29.95% relative to the other processes, or 0.331 kg 1,4-DCB. Aside from marine ecotoxicity, capture by trawler was responsible for over 10% of ozone formation (human health), ozone formation (terrestrial ecosystems), and terrestrial acidification.

Transport by lorry had the highest impact on terrestrial ecotoxicity, with 14.07% of the total impact. Aside from terrestrial ecotoxicity, transport by lorry was responsible for over 5% of global warming (6.13%), ozone formation (human health) (8.27%), ozone formation, terrestrial ecosystems (8.32%), and fossil resource scarcity (10.95%).

Ziegler et al.'s (2022) results highlighted fuel production and combustion impacts from capture fisheries (76–97%). Therefore, reducing the data inventory to these inputs still covers above three quarters of total environmental impacts. In the products from pelagic fisheries, which demonstrated the lowest fuel use intensity, fuel still represents 75% of fisheries emissions and approximately a third of total supply chain emissions (Ziegler et al., 2022).

The processes entitled "transport" and "transport: reefer" contribute the smallest proportion of environmental impacts, with less than 1% of impact in all categories. Transport by reefer describes the process of freezing the product across its journey from Norway to Portugal. Out of all the endpoint categories, this process is responsible for the greatest impact in ozone formation (human health) and ozone formation (terrestrial ecosystems) at 0.75% of impact in both categories. Transport: refers to the last step of the journey of codfish from the processing facility to the grocery store. Of all midpoint impact categories, this process is responsible for the highest relative impact in fossil resource scarcity (0.29%).

Aragão et al. (2022), also reported fishing as the largest contributor to emissions from hake supply chain in Spain, a fish from the same taxonomic order as codfish. The total carbon footprint of the hake supply chain accounted 681 kt CO_2e, where fishing contributes to 67% and transport to 33%.

IMPACT ASSESSMENT: DAMAGE ASSESSMENT CATEGORIES (ENDPOINT)

Endpoint analysis was also conducted to synthesize the damage in each of the 18 impact categories into three primary categories: impact on resources, emissions, and human health.

Error! Reference source not found. displays the percent impact of each of the six processes has on the three endpoint categories relative to the other processes involved.

Figure 5: Relative Environmental Impacts on Endpoint Damage Categories

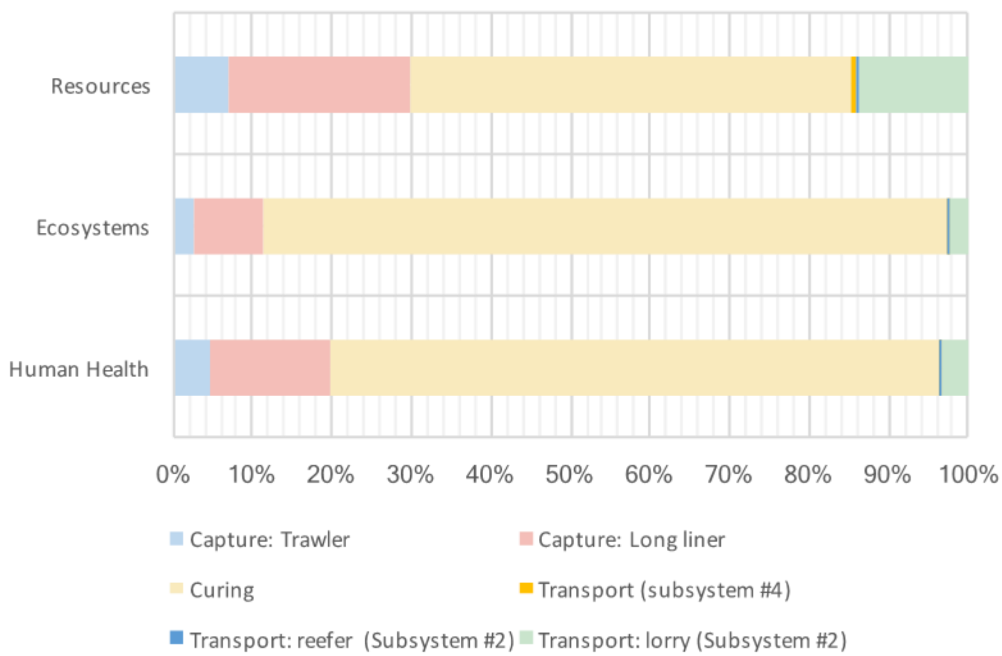


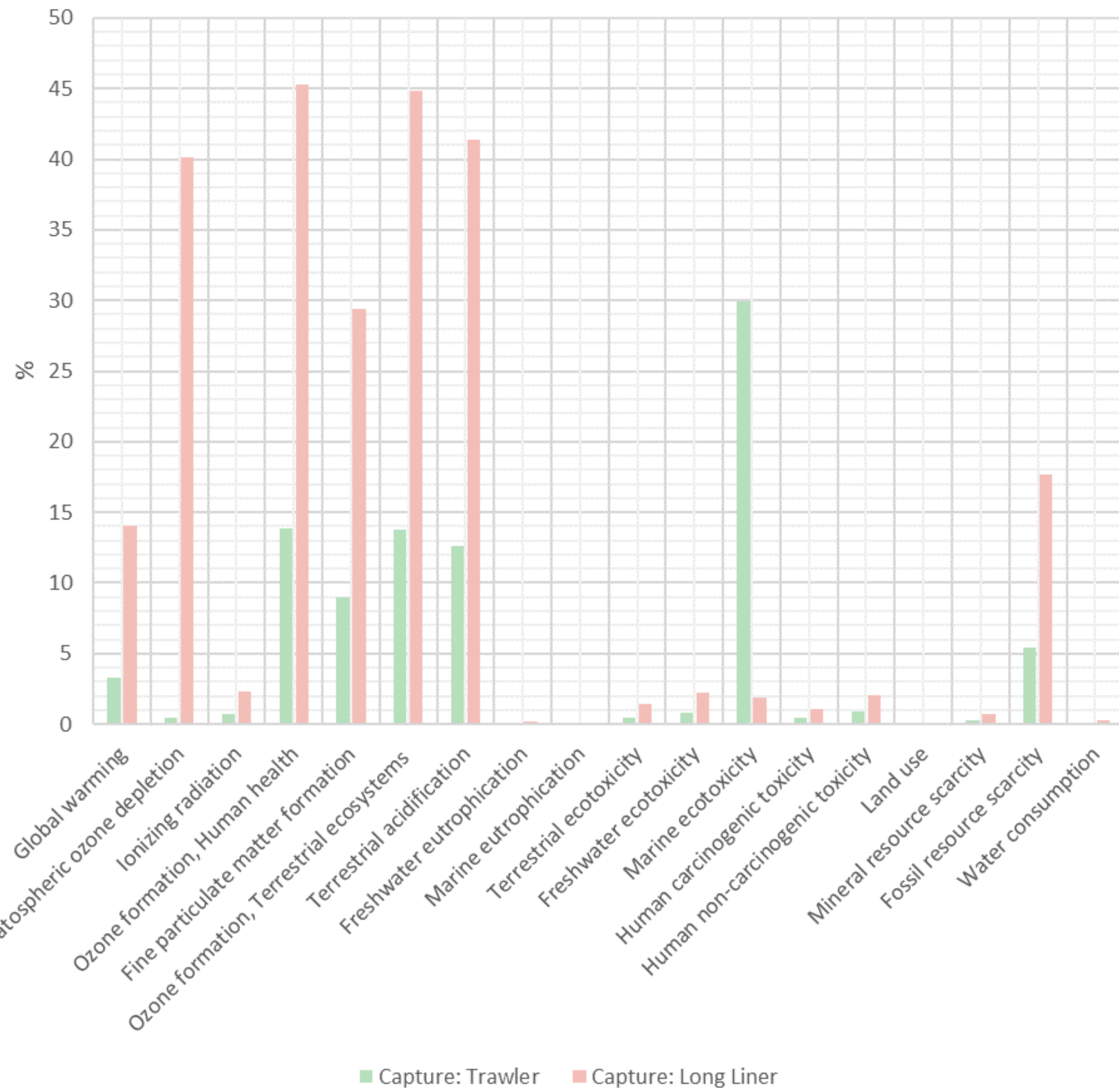
Figure 5 shows that over the course of the life cycle, curing is once again responsible for the greatest proportion of impact by far in all three categories. Of the three, curing is responsible for the highest percent of impact on ecosystems (85.94%), then human health (76.26%), and then resources (55.56%). Second to curing, capture by long liners had the greatest relative impact in each category, at 22.89% for resources, 15.38% for human health, and 8.93% for ecosystems.

Capture by trawler was also responsible for a significant portion of damage in each category, with 6.96% for resources, 4.53% for human health, and 2.56% for ecosystems. Transport by lorry was responsible for a significant proportion of the resource's endpoint category at 13.73%.

An examination of damage categories reveals that, in total, the production of 1 FU of codfish contributes 0.0000438 disability-adjusted life years (DALY) to the damage category of human health. One DALY represents the equivalent of the loss of one year of full health, so the production reduces a human lifespan by 0.0000438 years of perfect health. Regarding ecosystems, the production of 1 FU results in a reduction of 0.000000147 species per year. For scale, this is approximately equal to 15 species per kg per 100 million years. When it comes to resources, the production of 1 FU of codfish uses approximately 0.0996 USD.

In the SimaPro analysis, capture by long-lining and by trawling were weighted to represent the proportion of landed cod by fishing technique. Trawling was weighted about 3.22 times greater than long lining to represent the actual ratio of the two fishing types in Norway. Despite being weighted around three times the values included for long lining, the relative impact for long lining is greater than that of trawling for every midpoint impact category except ecotoxicity (Figure 6). Long lining is also consistently more impactful than trawling in each endpoint category. Other studies regarding the environmental impacts of seafood products have highlighted the fishing harvesting activities as a major contributor for most impact categories (Vázquez-Rowe et al., 2011).

Figure 6: Environmental Impact of Capture with Trawler Compared to Long Liner (Midpoint)



CRITICAL PROCESSES AND RECOMMENDED IMPROVEMENT ACTIONS

The results reveal that curing is overwhelmingly responsible for most of the environmental damage associated with the production and importation of codfish in Portugal. This means that targeting intervention techniques to reduce impacts at the curing stage of the process may be most effective. For example, improving the efficiency of the last step of transportation will not influence the same scale as an intervention at the curing stage, once environmental hazards associated with the last subsystem of the production process are responsible for less than 1% of impact in all 18 damage categories. In particular, the curing process has huge effects on freshwater and marine eutrophication, land use, and water consumption.

In addition to the curing process, the fishing process is critical due to its large proportion of environmental effect in key categories. Fishing activities are responsible for a large proportion of ozone formation and depletion. Although long lining tends to have a greater effect on most midpoint and all endpoint damage categories, trawling is responsible for a significant proportion of marine ecotoxicity, so interventions to trawling may involve targeted techniques to reduce the ecotoxicity of the process.

Regarding the capture of codfish, the comparative analysis of the two processes shows that long lining has a significantly greater impact on all midpoint damage categories except marine ecotoxicity. Long lining is associated with greater impact to human health, ecosystems, and resources. Therefore, a transition to trawling-based fishery activity may reduce the impacts associated with the capture stage of production. Although trawling is associated with significantly greater impacts on marine toxicity, its significantly smaller impact on other categories suggests it may be a more sustainable fishing technique. To reduce levels of ecotoxicity associated with trawling vessels, biocide-free paint can be adopted as an alternative to anti-fouling paints (Ytreberg et al., 2021).

The fishing stage of production is particularly associated with high rates of ozone production and stratospheric ozone depletion. Thus, an intervention to reduce ozone production from shipping vessels could significantly reduce the ozone formation and depletion associated with fishing. A LCA of a pelagic fishing fleet found that greater than 92% of the contribution to all impact categories was associated with the fuel burned (Sandison et al., 2021). Thus, interventions should focus on reducing the amount of fuel burned by each ship, whether this means improving fuel efficiency, or reducing mileage traveled by ships.

The transit from Norwegian fisheries to Portuguese processing facilities has a relatively large impact on marine ecotoxicity, ozone formation and terrestrial acidification, global warming, and fossil resource scarcity. The impacts specifically associated with ozone, global warming, and fossil resource scarcity are likely related to the combustion of diesel and subsequent emissions. Simple techniques to improve vehicle efficiency include reducing vehicle speed to reduce drag, keeping tires inflated, reducing AC usage, and reducing engine idling (Vaezipour et al., 2015).

One way to cut down the emissions related to this stage of transport is to reduce the distances traveled. The 4,000 km journey from Norway to Portugal certainly amplifies the impact of this stage of the process. Since Atlantic cod is not available in the warmer seas closer to Portugal, this intervention would likely mean significantly reducing the quantity of codfish that is imported into Portugal. This would certainly be an effective way to reduce the footprint of transit. However, codfish plays a major role in Portuguese cuisine and cultural identity. Cutting codfish importation would require a transformation of the consumption habits of hundreds of thousands of Portuguese people. A social mobilization on such a scale is not a feasible or efficient way to ascertain the intended environmental impacts. This is only amplified by the fact that this stage of processing is not responsible for the most significant portion of environmental impacts in any category. Thus, improvements to the materials used and technological efficiency in capture and curing may be a more efficient way to improve the environmental footprint of codfish production.

Curing is responsible for the greatest portion of waste produced. Thus, it follows that curing techniques should be optimized to reduce unnecessary energy and material consumption through the processing of codfish. Different types of waste at a cod production company could be generated: overproduction; waiting time; transport and excessive movement; overprocessing (such as storage, reprocessing, and inspections); and excess stock (Coppola et al., 2021). In particular, disorganization throughout the factory may result in repeating work that has already been done, such as relabeling batches when a product switches to another machine. This would result in wasted material, labor, and time. Increasing the efficiency of production by redesigning and organizing processing done at the factory is recommended to reduce the energy and materials required throughout the processing stage and ultimately reduce the damage to the environment.

Additionally, sustainable stocks, environmental impacts and effective management are the pillars to achieve sustainable codfish production. In particular, the Marine Stewardship Council (MSC) fisheries standard assesses if a fishery is well-managed and sustainable. If a fishery is certified, its catch can be sold with the blue MSC label, with better protections for marine life and stronger fisheries management and compliance requirements. MSC certified fisheries recorded more than 2,225 different improvements by March 2023. Performing one action can produce multiple improvements. For example, modifying gear types can reduce bycatch of a range of species. Therefore, improvements can show benefits in the protection of endangered and threatened species and habitats and fishery management. (Marine Stewardship Council, 2024).

LIMITATIONS

One limitation of this study is related to the fluctuation in product weight over the life cycle of codfish. As codfish undergoes the processing steps outlined in the methods section, its weight fluctuates. This means the units collected in the life cycle inventory are associated with the relative weight of the codfish at that stage in the process. Therefore, values throughout the fishing stage may be associated with the weight of 1kg of landed cod, while values collected at the curing stage are relative to the reduced weight of the codfish at this stage in production. The inability to account for changes in product weight may skew results.

Another limitation is the inability to account for the ecosystem impacts of fishing techniques, particularly trawling. Although this assessment concluded that trawling is a more environmentally sustainable practice than long-lining, trawling is hugely damaging to the environment. Trawling can affect an area of 1711 m^2 of the sea floor per FU of cod. This practice can damage the animals and habitats that are towed over, particularly the sedimentary living organisms on the seafloor (Avadí & Fréon, 2013). Typically, marine ecologists study seafloor impacts by collecting small samples from the bottom of the sea (Sandison et al., 2021). Because SimaPro software cannot account for ecosystem effects of trawling practices, the impacts of trawling on the seafloor are not included within the environmental impacts, which may lead to an underestimation of environmental effect of the fishing stage, particularly for trawling. The present work found that trawling had a much more significant impact when it comes to ecotoxicity. However, this study concluded that trawling was a more sustainable procedure since it had significantly smaller impact in all other midpoint impact categories. However, trawl fishing is highly stressful for cod. As more cod are captured, space becomes scarce, pressure is higher, and the fish are severely crowded. Research has demonstrated that shorter crowding time and more space during trawl capture followed by reduced slaughter stress can improve the quality of cod fillets. One solution to this issue is the introduction of waterfilled tanks where cod can be kept alive after being caught (Svalheim, 2018).

Conclusions

This study explored the environmental effects of codfish, fished by trawling and long lining in Norway, transported by lorry to Portugal, then dried, salted, and sold in Portuguese grocery stores. The results indicated that for codfish, the stage with the greatest effect on the majority of impact categories was curing. Midpoint analyses revealed curing to be responsible for over 99% of the environmental impacts in freshwater (0.02 kg P eq) and marine (0.00381 kg N eq) eutrophication, land use (8.8 m^2a crop eq), and water consumption (0.243 m^3). Nevertheless, fishing by trawling and long lining also had significant environmental impacts regarding ozone formation and ozone depletion. Moreover, endpoint analysis also showed that curing had the greatest effect on all endpoint categories, with the greatest impact on the ecosystem's endpoint category (85.94%).

This finding emphasizes the need to identify techniques to improve the sustainability of the curing process that codfish undergoes. Fishery certification plays an important role in sustainable stocks, environmental impacts, and effective management improving. Herein, indicators could address how sustainable a fishery is and provide guidelines for further improvements in a more detailed manner. Solutions may include the improvement of codfish processing facilities, efficiency by reorganizing workflows, and taking stock of unused capital. Nevertheless, further research on production using novel technologies and curing techniques is also needed.

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AUTHOR BIOGRAPHIES

A. Frost: Undergraduate student at the School for International Training in the Sustainability and Environmental Justice Program in Portugal (from September to December 2022). Degree in Public Health and Environmental Studies from Johns Hopkins University (Baltimore, Maryland, USA) and background in assisting non-profit organizations and small businesses in the areas of environment, community development, and food. Currently a Senior Associate at Oaktown Spice Shop, overseeing the sustainable sourcing of spices and actively promoting local businesses.

J. Almeida: PhD in Eco-Construction and Rehabilitation (2021) and a MSc in Environmental Engineering (2015) from NOVA School of Science and Technology, NOVA University Lisbon. Research work has focused on electro-based technologies development for critical raw materials recovery, harmful compounds removal and hydrogen production from environmental matrices. Joana also researched the reuse of secondary resources as construction materials and life cycle assessment. Currently is an Assistant Researcher at CENSE, NOVA School of Science and Technology.

J. Dionisio: MSC in Environmental Engineering from NOVA School of Science and Technology, NOVA University Lisbon. Joana had collaborated in a European research project related to circular economy and sustainable wastewater management. She has two years of experience in guiding students with the development of their master theses, including work coordination and laboratory support. Currently part of SIT Study Abroad team, as program coordinator in Portugal (2021).

R. Godina: Assistant Professor in Industrial Engineering and Management at NOVA School of Science and Technology | FCT NOVA, NOVA University Lisbon, Portugal and is an Integrated Research Member of the Research and Development Unit in Mechanical and Industrial Engineering (UNIDEMI), and LASI, Portugal. Authored or co-authored more than 165 indexed international journals, book chapters and conference proceedings papers. He is coordinator at UNIDEMI of the project M4ML - Mobility for Maritime Logistics.

C. Magro: Doctorate in Environment and Sustainability from NOVA School of Science and Technology. She conducts research on nanomaterials, sensors development, remote sensing, waste management and life cycle assessment. Her contributions (1 patent application, 23 articles and 4 book chapters) have culminated in a 10 *h-index*. Currently, Cátia assumes the role of Academic Director for SIT in Portugal, while continuing her research work at NOVA FCT and serves as a Mentor for the HiSeedTech association.