This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773330

Deliverable report for

GAIN

Green Aquaculture Intensification in Europe

Grant Agreement Number 773330

Deliverable D4.4
Report on the application of LCA

Due date of deliverable: 30/04/2021
Actual submission date: 21/05/2021

Lead beneficiary: UNIVE (Università Ca' Foscari Venezia)
Authors: Silvio Cristiano, Richard Newton, Hallstein Baarset, Leticia Regueiro, Christian Bruckner, Lars Svenningsson, Edouard Royer, & Roberto Pastres

WP4 – Eco-Intensification of aquaculture
Task 4.3: Sustainability assessment of eco-intensification

Dissemination Level:		
PU	**Public**	**Y**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document log

Version	**Date**	**Comments**	**Author(s)**
Version 1	20/10/2020	First draft: T4.3 updates	Silvio Cristiano
Version 2	03/03/2021	First advanced draft	Silvio Cristiano
Version 3	25/04/2021	Second advanced draft	Silvio Cristiano
Version 4	29/04/2021	Third advanced draft	Silvio Cristiano
Version 5	03/05/2021	Revision	Roberto Pastres
Version 6	14/05/2021	Revised document	Silvio Cristiano
Version 7	11/01/2022	Reviewed document	Silvio Cristiano

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Recommended Citation

Cristiano, S., Newton, R., Baarset, H., Regueiro, L., Bruckner, C., Svenningsson, L., Royer, E., & Pastres, R. (2021). Report on the application of LCA. Deliverable 4.4 Report on the application of LCA - GAIN – Green Aquaculture Intensification in Europe. EU Horizon 2020 project grant nº. 773330. 92 pp.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

GLOSSARY OF ACRONYMS

Acronym	Definition
BOD	Biochemical Oxygen Demand
CED	Cumulative Exergy Demand
COD	Chemical Oxygen Demand
CPUE	Catch per unit effort
DO	Dissolved Oxygen
EISI	Eco-Intensification Sustainability Index
FIFO	Fish In Fish Out
FM	Fish Meal
FO	Fish Oil
FU	Functional Unit
GAIN	Green Aquaculture Intensification
GWP	Global Warming Potential
HDPE	High-density polyethylene
HRT	Hydraulic Retention Time
ISO	International Organisation for Standardisation
LCA	Life-Cycle Assessment
LCIA	Life-Cycle Impact Assessment
LCI	Life-Cycle Inventory
LDPE	Low-density polyethylene
LHO	Low Head Oxygenator
NOK	Norwegian krone
OTE	Oxygen Transfer Efficiency
PFF	Precision Fish Farming
RAS	Recycling Aquaculture System
UV	Ultra-Violet
SHP	Salten Havbrukspark
SHS	Super-heated steam
SS	Suspended Solids
TRL	Tecnology Readiness Level
UNIVE	Università Ca' Foscari Venezia
UoS	University of Stirling
TN	Total nitrogen
WAS	Waister AS

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table of Contents

Deliverable D4.4
Report on the application of LCA
Task T4.3

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Executive summary

The objective of increasing the production and competitiveness of the aquaculture sector is matched with the quest for increased **sustainability**. The present deliverable shows the results of some **Life-Cycle Assessments** (LCA) aimed at evaluating the **environmental performances** of **selected novel eco-intensification systems and practices** developed in GAIN (WP1–WP2). Some benefits and margins for improvement of such innovations are discussed. Data are provided on **standard indicators** (carbon footprint, i.e. global warming potential; ecological footprint; stratospheric ozone depletion; terrestrial acidification; freshwater eutrophication; marine eutrophication; biochemical oxygen demand; mineral resource scarcity; fossil resource scarcity; cumulative exergy demand; land use; and water consumption).

The selected innovations include: new machinery and processes to treat **fish mortalities** and safely reuse these by-products as secondary resources; new machinery and processes to filter and dry **RAS reject water** so as to extract nutrients and biomass in general to be reinserted and valorised into other economic activities; the use of by-products from shellfish industry to replace plastic components as fillers in **RAS biofilters**; Precision Fish Farming innovations to optimise **oxygen supply** in trout farms. An input with one of the largest environmental impacts in aquaculture is also addressed, i.e. **fish feed**. Results suggest that:

- Innovations in fish mortality treatment and valorisation show extremely good environmental performances; the best performing eco-innovation is the one that recirculates energy in the fish farm and biomass in another food supply chain (pet food), with a lower use of non-renewable inputs; although the first feature stands out as the most crucial one, the intuitive benefits coming from the design of a more circular and renewable-based economy look here confirmed.
- Innovations in reject water treatment and valorisation show environmental savings ranging from –16% up to –67%, depending on the observed indicators; a slight increase is present instead regarding Water consumption, linked to a larger input, but such an increase is reduced thanks to efficiency of the rest of the innovation; no markedly better alternative emerges among end-of-life options, i.e. dried sludge reuse in fertilisers or as biomass for different energy transformations.
- Innovations on plastic filler replacement with waste mussel shell fillers in RAS biofilters allow for the saving of fossil fuels and implies some gains in most of the selected impact categories; in any case, however, the impacts related to the filling materials are two orders of magnitude lower than the overall impacts connected to a biofilter's operations in a RAS, thus environmental gains are quite limited; the scaling up of the eco-innovations from the lab scale to a pilot project plant one suggest possible improvements in all of the criticalities that have been illustrated so far, thus being likely to be worth further developments and consequent environmental assessments in future projects.
- Innovations for oxygen supply optimisation via precision fish farming-inspired sensors and automated valves suggest improved environmental performances when oxygen savings are relevant (–92%), while no improvement was detected with smaller oxygen savings (–13%); in both innovative scenarios, the indicator Mineral resource scarcity undergoes some marked worsening (+20% or more): here, the upstream resource requirements connected to the technological hardware do not offset the oxygen savings.
- Fish feed is dedicated a LCA review as an input with major environmental impacts.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

1. Introduction

Within the GAIN project, the objective of increasing the production and competitiveness of the aquaculture sector is matched with the quest for **sustainability** gains in compliance with EU regulations on food safety and environment.

This Deliverable 4.4 reports the results obtained in Task 4.3 "Sustainability assessment of eco-intensification", led by UNIVE in the period M19-42.

The development of our Eco-Intensification Sustainability Index (EISI) was addressed in parallel in Deliverable 4.3, led by UoS (Newton *et al.*, 2021).

The present deliverable focuses on the outcomes of the application of **Life-Cycle Assessment** (LCA). As planned since the project proposal, results of LCA analyses were also used for the development of EISI indicators.

As part of Task 4.3's planned activities, and specifically functional to **D4.3**, a Life-Cycle sustainability assessment was successfully performed – wherever data were available – on **selected novel eco-intensification systems and practices developed within GAIN**.

These systems were modelled on the basis of data and information provided by partners involved in work packages WP1 and WP2 who were actively engaged in the drafting of this report. Information was shared by email, informal conversations, and virtual technical meetings. in Figure 1.1.

The aim of the present study was to evaluate the **benefits and/or margins for improvement** of such innovative systems and practices.

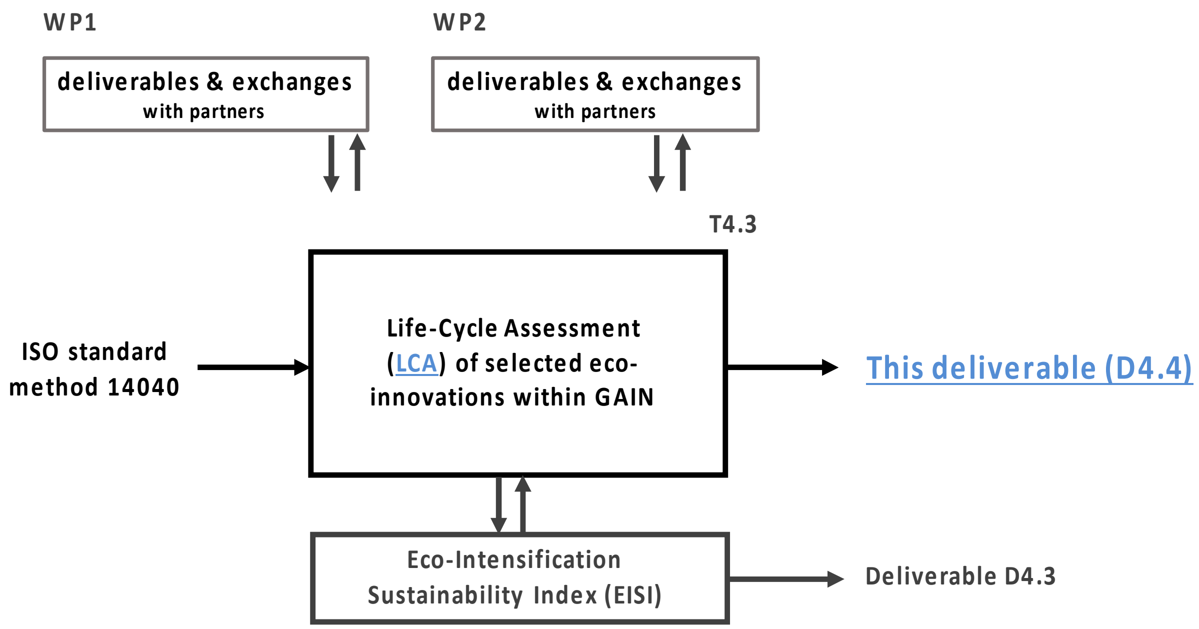


Figure 1.1 – Flow chart of information exchange for the production of the present deliverable D4.4

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

For each eco-innovation, data are here provided on standard indicators (carbon footprint, i.e. global warming potential; ecological footprint; stratospheric ozone depletion; terrestrial acidification; freshwater eutrophication; marine eutrophication; biochemical oxygen demand; mineral resource scarcity; fossil resource scarcity; cumulative exergy demand; land use; and water consumption), and compared with corresponding reference scenarios, i.e. the business-as-usual systems and practices that were meant to be improved.

Various Life-Cycle analyses were therefore performed to carry forward findings from business-as-usual and GAIN's eco-innovative scenarios. In the light of the higher level of detail and of the increased amount of information required to perform our environmental assessments for each and every scenario, **original spreadsheets and diagrams** were expressly designed and collaboratively filled in within Task 4.3.

As per the project description, in GAIN LCA was meant to provide data that would later be **functional** to the development of the novel Eco-Intensification Sustainability Index (EISI), based on LCA standard indicators of environmental impact. Such standard indicators were expected to include information about carbon, water, and land impacts, ozone depletion, eutrophication, and acidification emissions.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

2. Assessment method

2.1 Introduction to the standardised Life-Cycle framework

The Life-Cycle Assessment (LCA) method was used according to the ISO14040 standard (ISO, 2006). LCA allows for the **environmental accounting of anthropogenic impacts**, mostly related to productive activities. LCA is "a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials **processing, manufacture, distribution, and use**" (Muralikrishna & Manickam, 2017), as also illustrated in Figure 2.1.

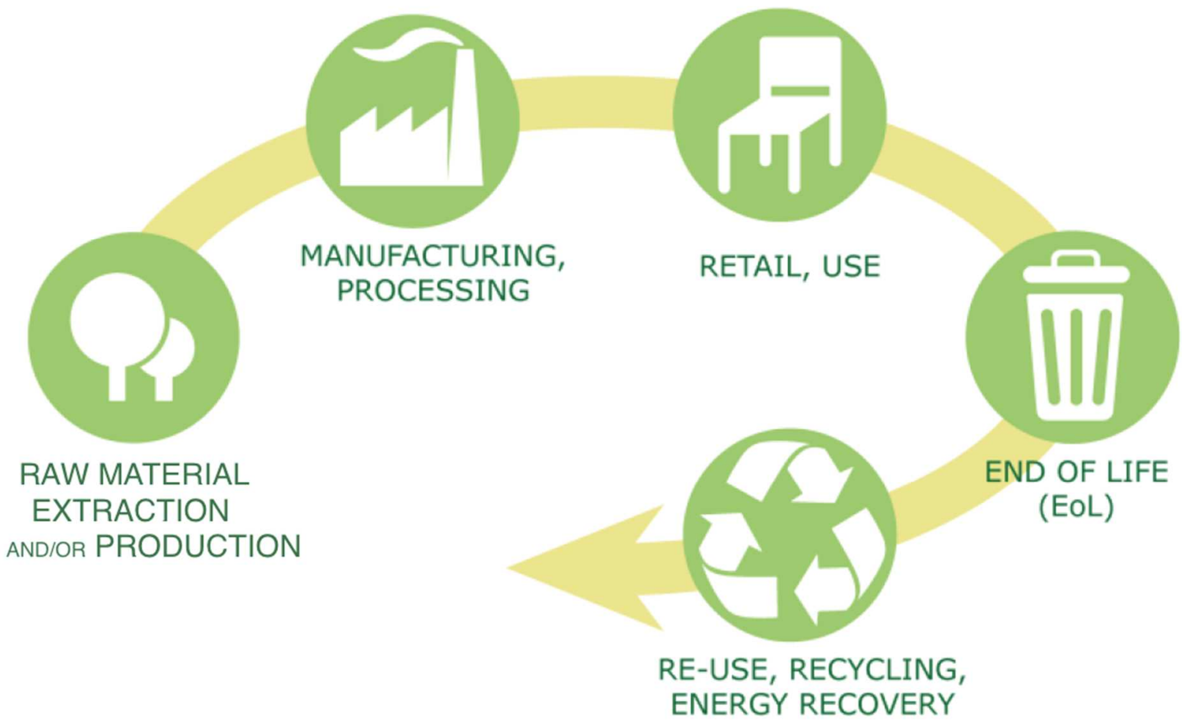


Figure 2.1 – "Life cycle stages modelled in LCA" (adapted from European Commission, 2019)

In the acquaculture sector, Life-Cycle Assessment is a widely recognised and implemented environmental assessment method, as reviewed and evaluated e.g. by Henriksson *et al.* (2012), Bohnes & Laurent (2019), and Bohnes *et al.* (2019). LCA's basic rationale is reported in Figure 2.1.

In this deliverable, estimated environmental impact data following the LCA of selected GAIN's eco-innovations are presented. In some cases, inventories include also labour estimate and financial data which cannot be processed through an LCA evaluation but could contribute to the interpretation of results and, later on, be used to complement the LCA with an eMergy assessments (see e.g. Maiolo *et al.*, 2021).

A more detailed illustration of the LCA steps for the calculation of the Life-Cycle Impact Assessment (LCIA) indicators is offered in Figure 2.3, meant to guide the reader throughout the present deliverable.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

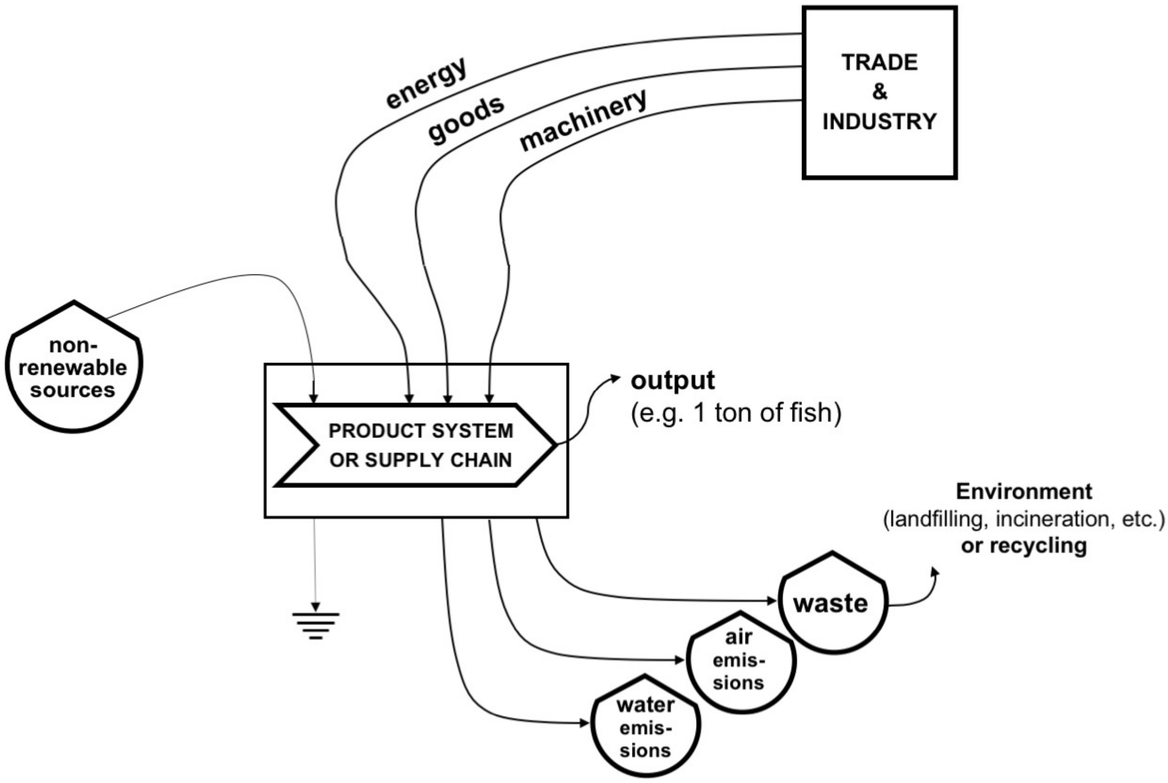


Figure 2.2 – "Inputs and impacts from aquaculture that can be accounted for in Life-Cycle Assessment" (Rosenthal *et al.*, 2020)

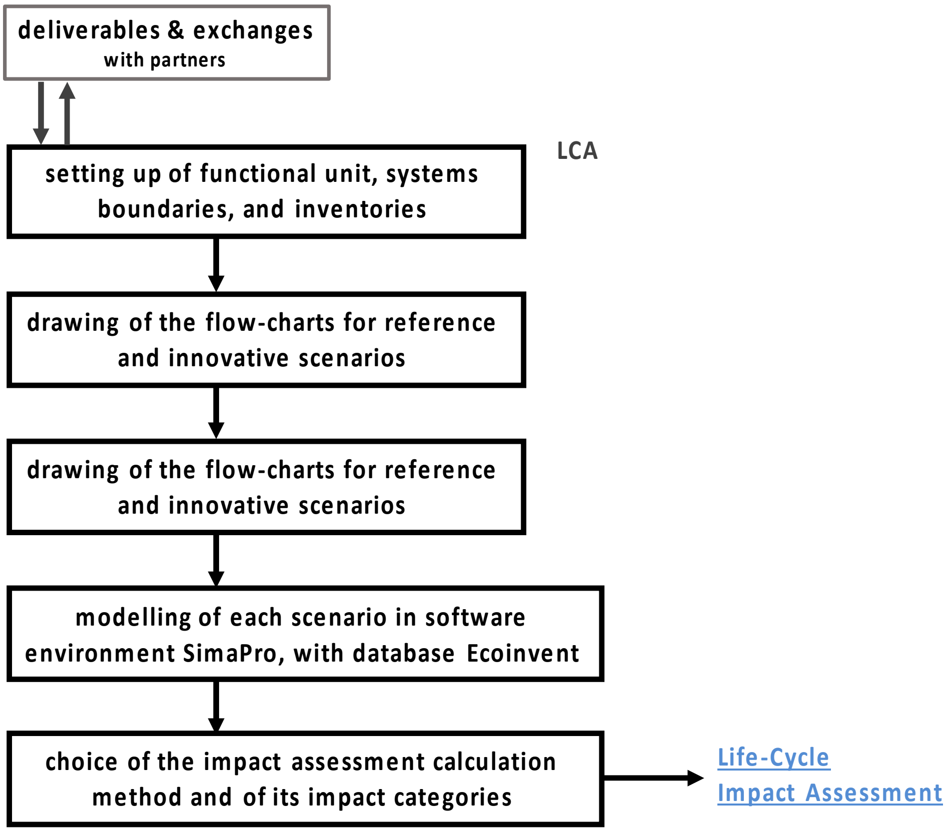


Figure 2.3 – LCA steps for the calculation of the Life-Cycle Impact Assessment indicators

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

2.2. Assessment rationale, flow-charts, software, database, and allocation

The general rationale for LCA modelling and accounting choices was not to overestimate benefits from eco-innovations; as a consequence, this can be meant as a **cautious assessment**. A basic conceptual model of each case study (**flow chart**) was drafted manually and through basic computer-aided design, and later implemented quantitatively. The LCAs were carried out using the world leading software package **SimaPro**[1]. Secondary data were obtained from the **Ecoinvent** 3.1[2] database. (Wernet *et al.*, 2016). The allocation was based on the cut-off principle, i.e. excluding some inputs that are not significant for the product system at hand, at a system (not unit) level, therefore **Cut-off, S**.

2.3. LCIA: calculation methods, impact categories, and indicators

The indicators to calculate were selected among standard impact categories, as planned in the project description. Impact categories included: carbon, water, and land impacts, ozone depletion, eutrophication, and acidification emissions. Standard indicators were chosen accordingly. The selected indicators are listed in Table 2.1, which presents in the second column the units of the characterisation factors and in the third one the estimation methods.

Table 2.1. Selected Life-Cycle Assessment indicators, units, and estimation methods

Indicator	Unit	Estimation method
Carbon footprint, as **Global Warming Potential** (GWP), IPCC GWP 100a	equivalent mass of carbon dioxide (**kg $CO_{2\,eq}$**)	United Nations' Intergovernmental Panel on Climate Change (IPCC), 100-year time span (Forster *et al.*, 2007)[3]
Ozone depletion, as **Stratospheric ozone depletion**	equivalent mass of trichlorofluoromethane (**kg CFC-11** $_{eq}$)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Terrestrial acidification	equivalent mass of sulphur dioxide (**kg $SO_{2\,eq}$**)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Freshwater eutrophication	equivalent mass of phosphorus (**kg P_{eq}**)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Marine eutrophication	equivalent mass of nitrogen (**kg N_{eq}**)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Mineral resource scarcity	equivalent mass of copper (**kg Cu_{eq}**)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Fossil resource scarcity	equivalent mass of crude oil (**kg oil** $_{eq}$)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Water consumption	volume (**m^3**)	ReCiPe 2016 Midpoint (Huijbregts *et al.*, 2017), egalitarian (E)
Cumulative Exergy Demand	**MJ**	Bösch *et al.* (2007)
Land occupation	annual areal occupation (**m^2 * a**)	Selected LCI results (Frischknecht *et al.*, 2007)
Biochemical Oxygen Demand	required oxygen mass, (**kg**)	Selected LCI results (Frischknecht *et al.*, 2007)
Ecological footprint, as **Land use**	points (**Pt**)	Ecological Footprint Method (adapted) V1.00 / Global (2010) (Ewing *et al.*, 2010)

[1] https://simapro.com/

[2] https://www.ecoinvent.org/database/older-versions/ecoinvent-31/ecoinvent-31.html

[3] GWP could be also estimated by method ReCiPe, used for the following indicators; opting for IPCC is due to the preference for a direct reliance on the most important global institution dealing with climate change.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

In ReCiPe 2016, the **egalitarian** (E) perspective targets long-term impacts and is based on precautionary principles.

Cumulative Exergy Demand includes both **renewable and nonrenewable** sources.

Additional impact categories and indicators were used in Chapter 7 and are presented at the beginning of that chapter.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

3. LCA of GAIN's eco-innovations for fish mortalities valorisation

Based on GAIN's previous deliverables **D2.2** (Baarset & Johansen, 2019) and **D2.6** (Baarset *et al.*, 2021), and refined through direct, fruitful, and reiterated information exchange with GAIN partner Waister AS, three scenarios of mortality disposal were designed as a conceptual basis and quantitative reference for the environmental accounting:

- **scenario A**: ensilage (**Figure 3.1**);
- **scenario B**: super-heated steam (SHS) dryer and cooling water (**Figure 3.2**);
- **scenario C**: SHS dryer and a cooling medium other than water (**Figure 3.3**).

Building upon additional data made available by GAIN partner Waister AS (Baarset, 2021), three end-of-life product valorisation options are also defined for both scenarios B and C, thus creating sub-scenarios B1, B2, B3, C1, C2, and C3. The end-of-life options are described below in section 3.1.5.

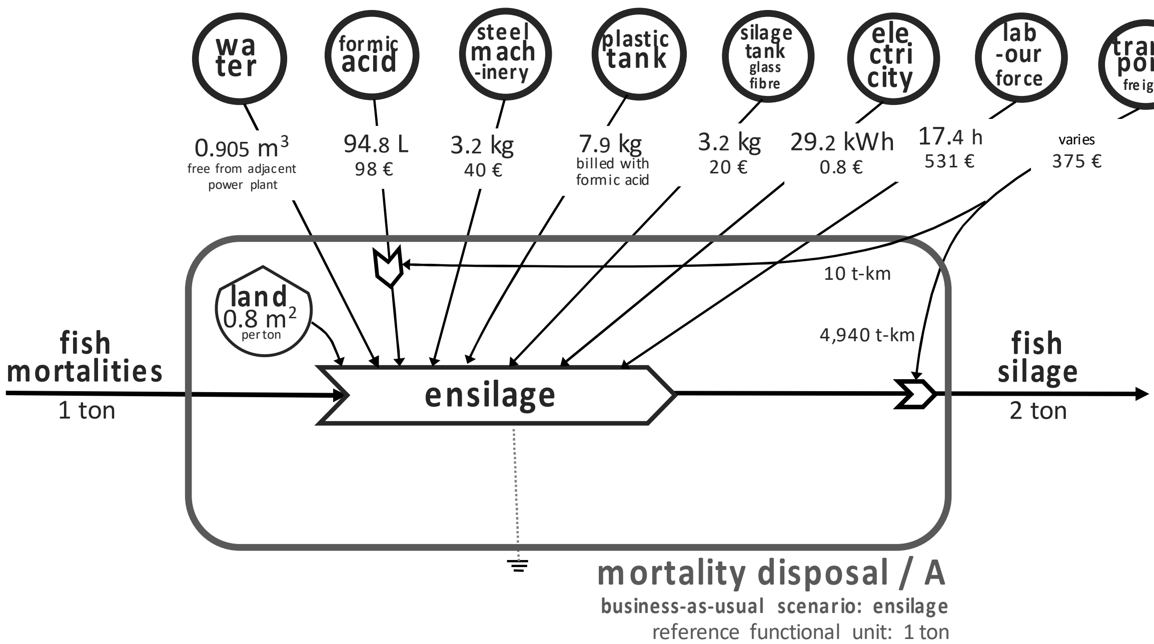


Figure 3.1 – Conceptual and quantitative diagram for fish mortality disposal scenario A

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

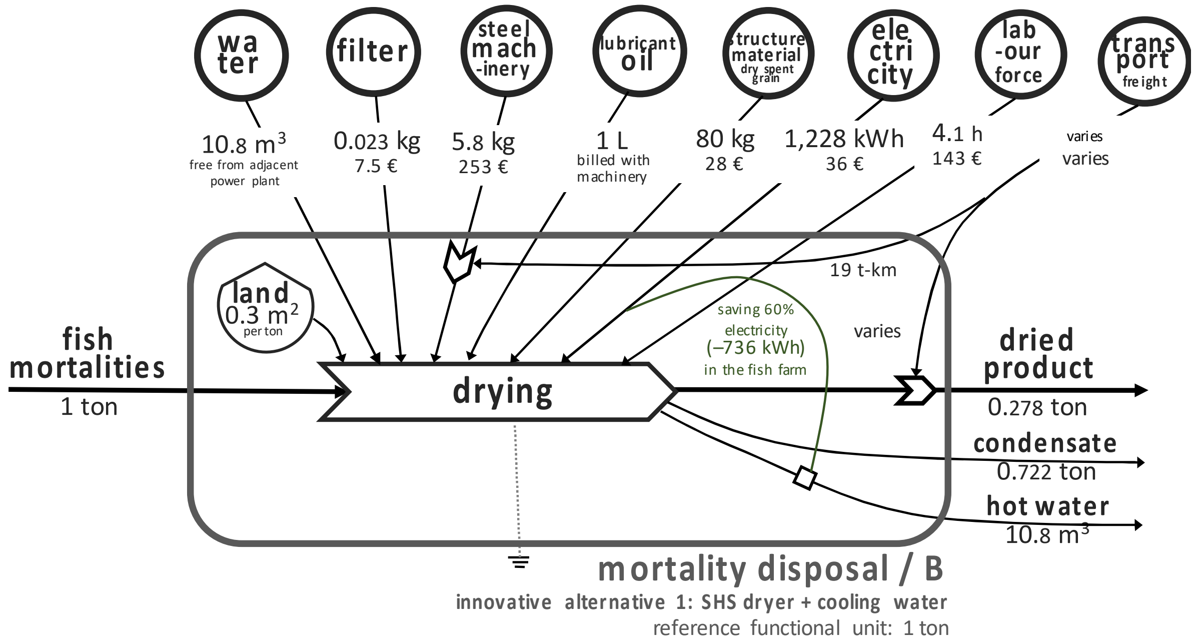


Figure 3.2 – Conceptual and quantitative diagram for fish mortality disposal scenario B

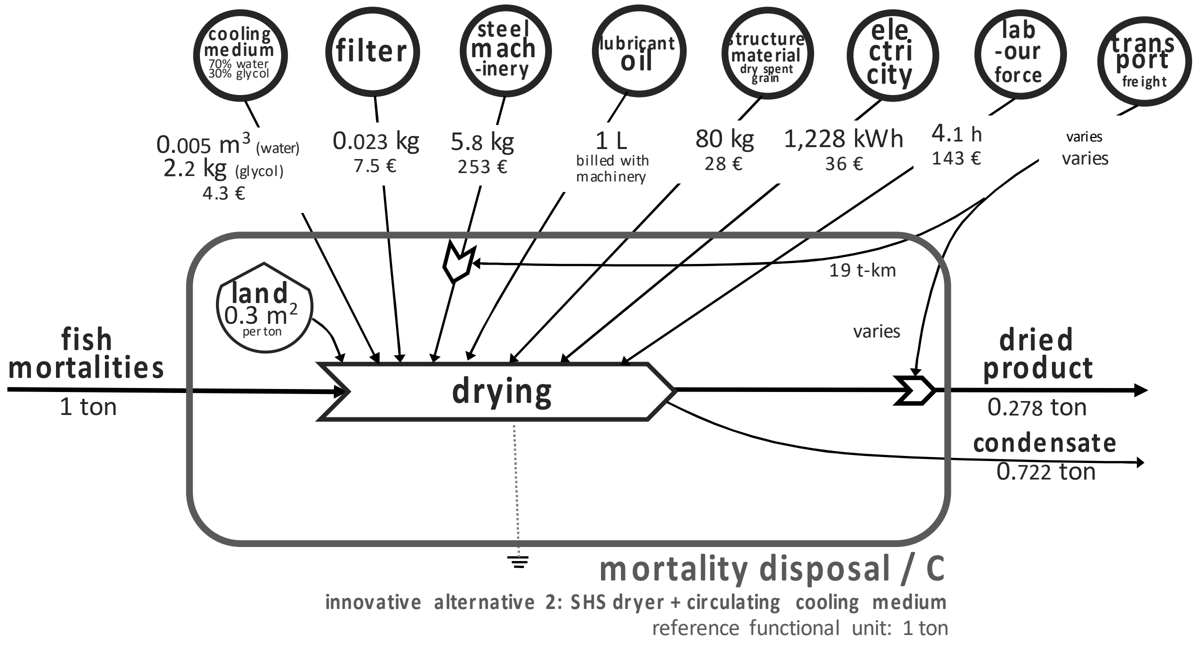


Figure 3.3 – Conceptual and quantitative diagram for fish mortality disposal scenario C

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

3.1 Main eco-innovations for mortality disposal

Currently, the main technology for processing fish mortality is the ensilage, according to which formic acid has to be used and hazardous substances[4] disposed of and transported away from the plant (more details in **D2.2**, Baarset & Johansen, 2019). This business-as-usual technology is assessed as scenario A.

GAIN process aims, instead, at drying and sanitising fish biomass using a superheated steam drying technology, with mechanical fluidisation of the product. The process was optimised by GAIN partner Waister; the results here presented are based on the performance of a prototype – "Waister 15" device (Figures 3.4–3.5) – as described in **D2.6**. The main advantages of such innovation lie in the improvements in the workers' safety and in overall reduced operational monetary costs (more details in **D2.2**, Baarset & Johansen, 2019; and in **D2.6**, Baarset *et al.*, 2021). This innovation is assessed with two different cooling media: just water and a mix of glycol (30%) and water (70%); the former is addressed in scenario B, the latter in scenario C. Here, an SHS / Waister steam dryer is used.

Figure 3.4 – "Development stages in drying technology for mortalities" (D2.6, Fig. 3, Baarset *et al.*, 2021)

Figure 3.5 – "Mortalities in inlet buffer of Waister 15" (adapted from D2.6, Fig. 6, Baarset *et al.*, 2021)

[4] Able to cause acid etching to the skin, lungs, eyes, etcetera; in tanks, it may produce gases that are harmful to breathe and that can be explosive.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

3.1.1 Main features of eco-innovations for mortality disposal compared to business-as-usual

In the process of grinding the fish mortalities, when entering the ensilage tank water and formic acid are added to the fish; this means the volume of ensilage increases compared to original fish volume. Instead, no water nor formic acid are added while fish mortalities are ground upon their entering the drying chamber in the Waister superheated steam dryer. The dried fish product is a microbiologically stable powder that may be stored and transported using ordinary truck transport, while the ensilage needs transport in special tank trucks. These tank trucks need thorough cleaning – one hour of work and some acid cleansing products – between each transport to prevent any contamination. Also, weight and volume of the output of the treated fish mortalities in the innovative scenarios (B and C) is one order of magnitude smaller than the corresponding weight and volume of business-as-usual ensilage (scenario A). More details about these features are offered in **D2.2** (Baarset & Johansen, 2019) and in **D2.6** (Baarset *et al.*, 2020).

Data about the GAIN eco-innovation at hand are referred to Helgeland Smolt AS, site Reppen, Norway, which is a modern RAS smolt farm with RAS technology delivered by Veolia Krüger Kaldnes. Mortalites are collected from each tank. There is an automatic transport system to collect all mortalities to the "waste room". The mortalities are transported by water into the transport system. Mortalities are then separated from the excess (transport) water. Currently, this is manually sieved and put into the inlet hopper of the Waister dryer. A system for automatic separation of mortalities and excess water will be essential if the process is to be automated.

3.1.2 End-of-life product valorisation options

Three different options to valorise the end-of-life product obtained through the GAIN's eco-innovation at hand (Baarset, 2021) were investigated. Such options are described below, and in the present assessment result in sub-scenarios B1, B2, B3, C1, C2, and C3 as illustrated in Figures 3.6–3.11.

<u>Option 1 – Animal feed ingredient for pet food</u>

The dried product leaving the system is used as an animal feed ingredient for pet food. For the Norwegian demonstration plant at issue, this implies transportation by road for 1,187 km, with such a travel costing approximately 35 €/ton to be paid by the receiver (i.e. the pet food producer), and with the dried product exhibiting a value of approximately 1,350 €/ton upon arrival.

<u>Option 2 – Bio-energy at cement factory</u>

Dried fish mortalities are used as biomass to produce bio-energy at a cement factory. In our case study, this implies transportation by road for a distance of 351 km, costing approximately 12 €/ton, to be paid by the fish farm. When arriving at the cement factory, the product is worth 27 €/ton.

<u>Option 3 – Biogas substrate</u>

The dried output is used as a biomass for gasification. After travelling 1,735 km to Denmark by road (with this trip costing approximatively 50 €/ton and being paid by the fish farm), the value of the product is 0, i.e. it is received free of charge and not paid as a secondary resource.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

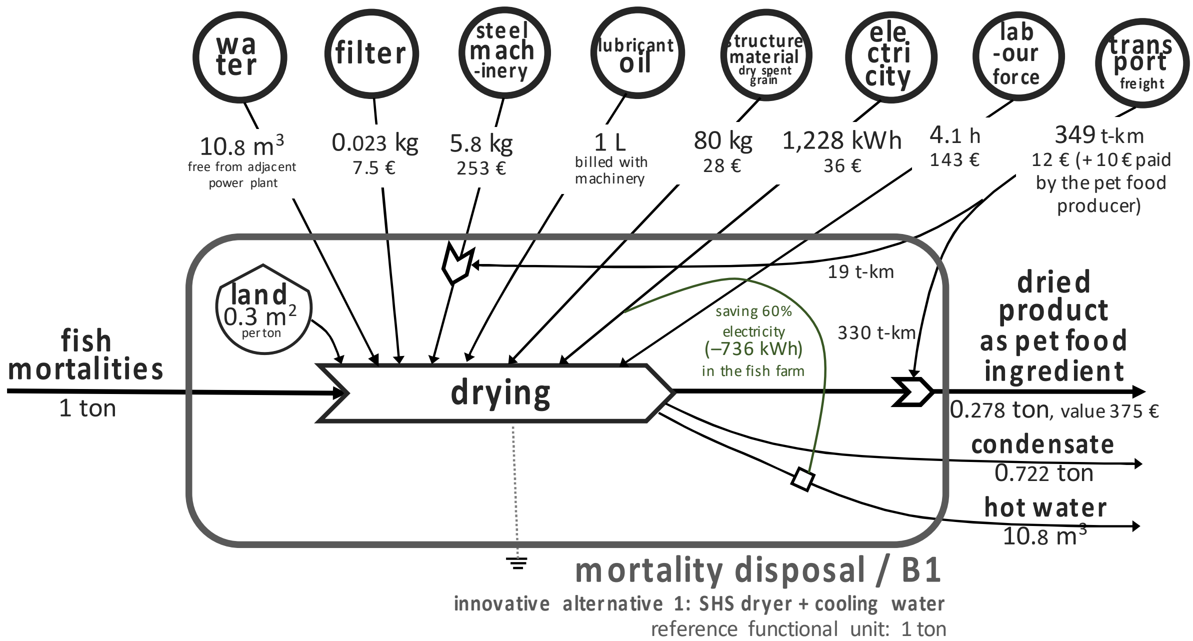


Figure 3.6 – Conceptual and quantitative diagram for fish mortality disposal sub-scenario B1

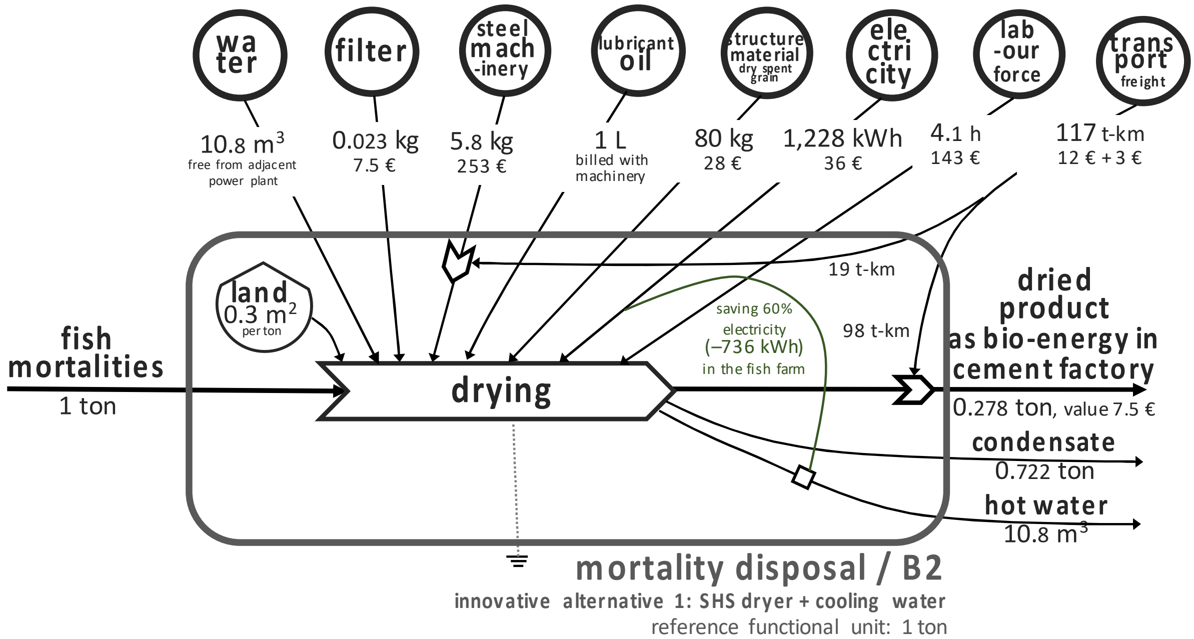


Figure 3.7 – Conceptual and quantitative diagram for fish mortality disposal sub-scenario B2

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

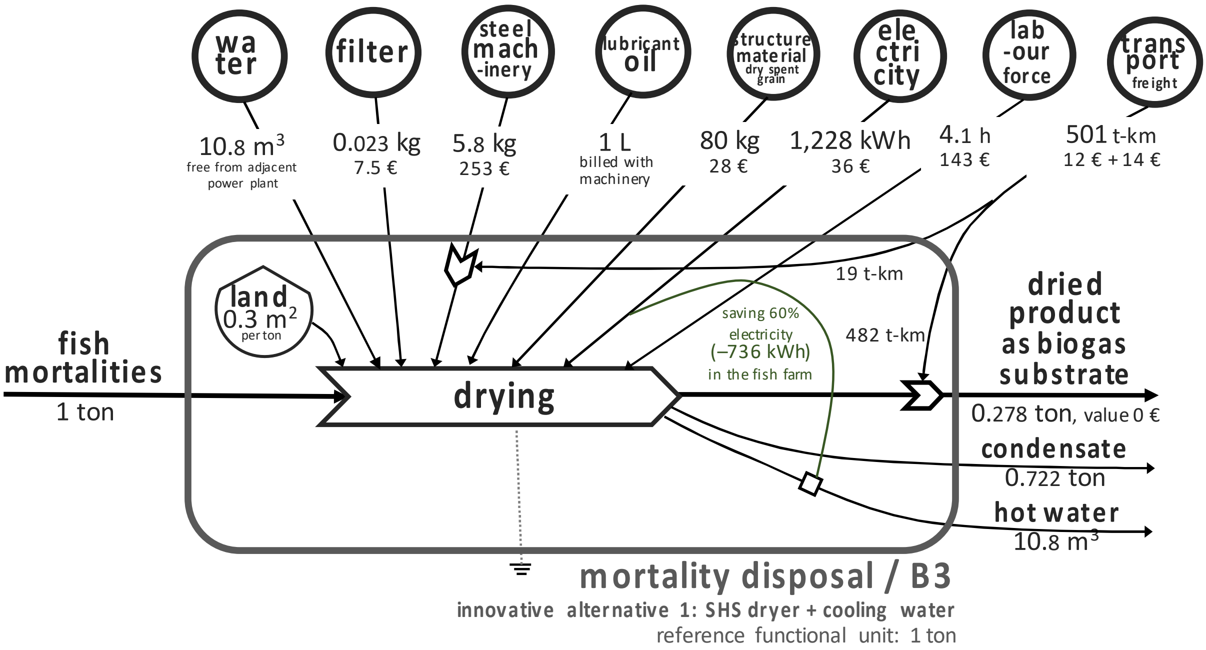


Figure 3.8 – Conceptual and quantitative diagram for fish mortality disposal sub-scenario B3

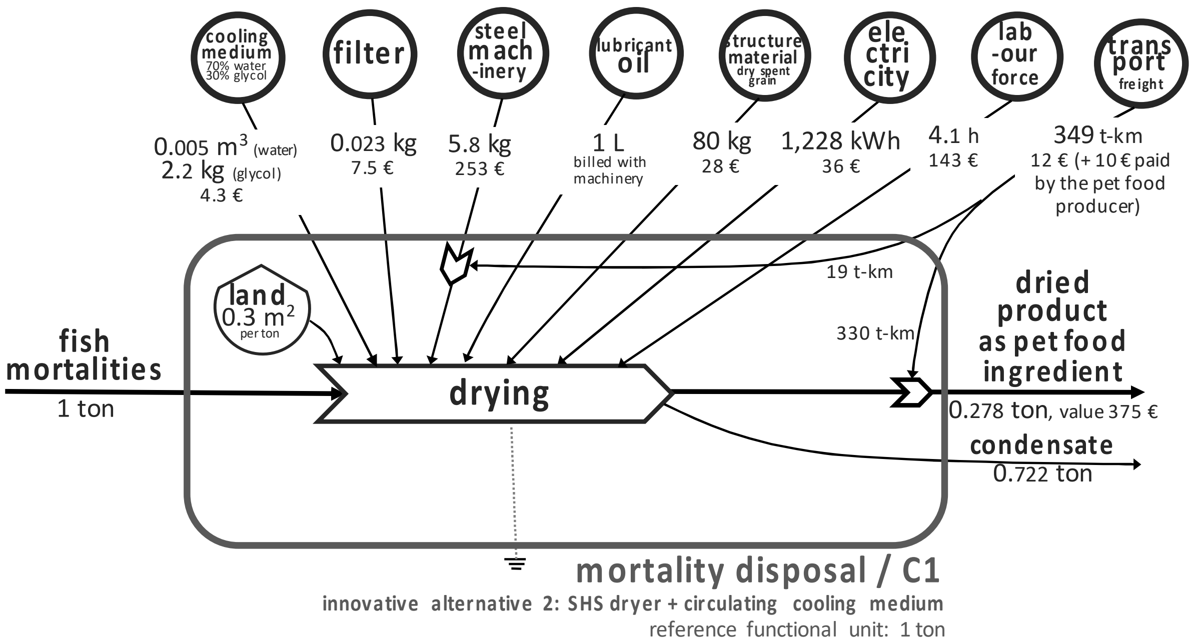


Figure 3.9 – Conceptual and quantitative diagram for fish mortality disposal sub-scenario C1

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

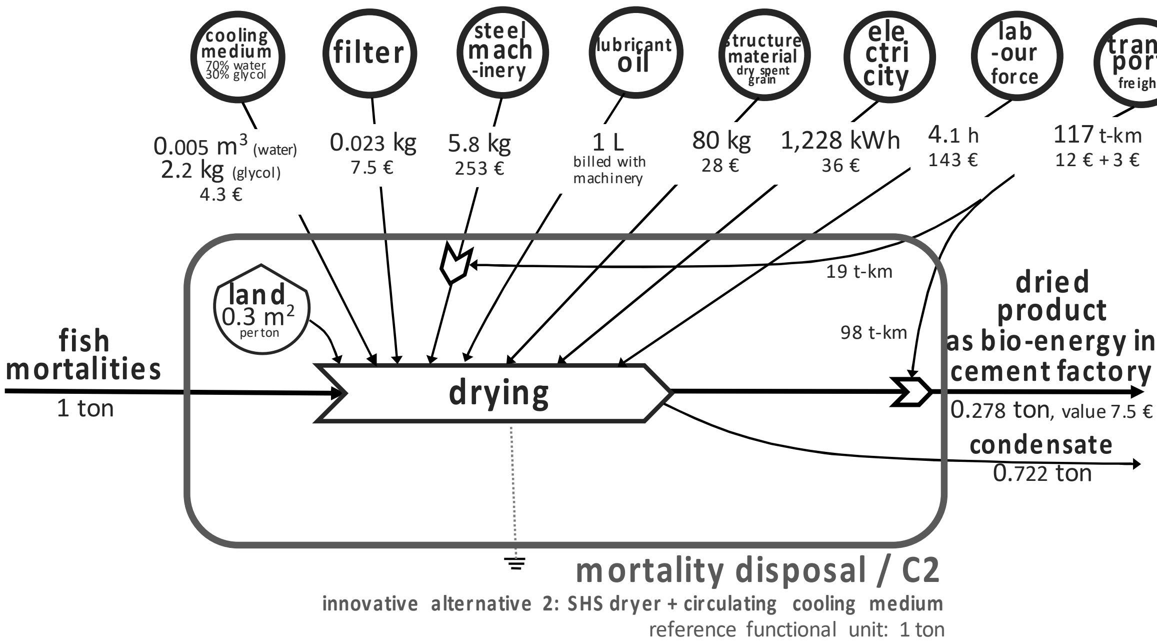


Figure 3.10 – Conceptual and quantitative diagram for fish mortality disposal sub-scenario C2

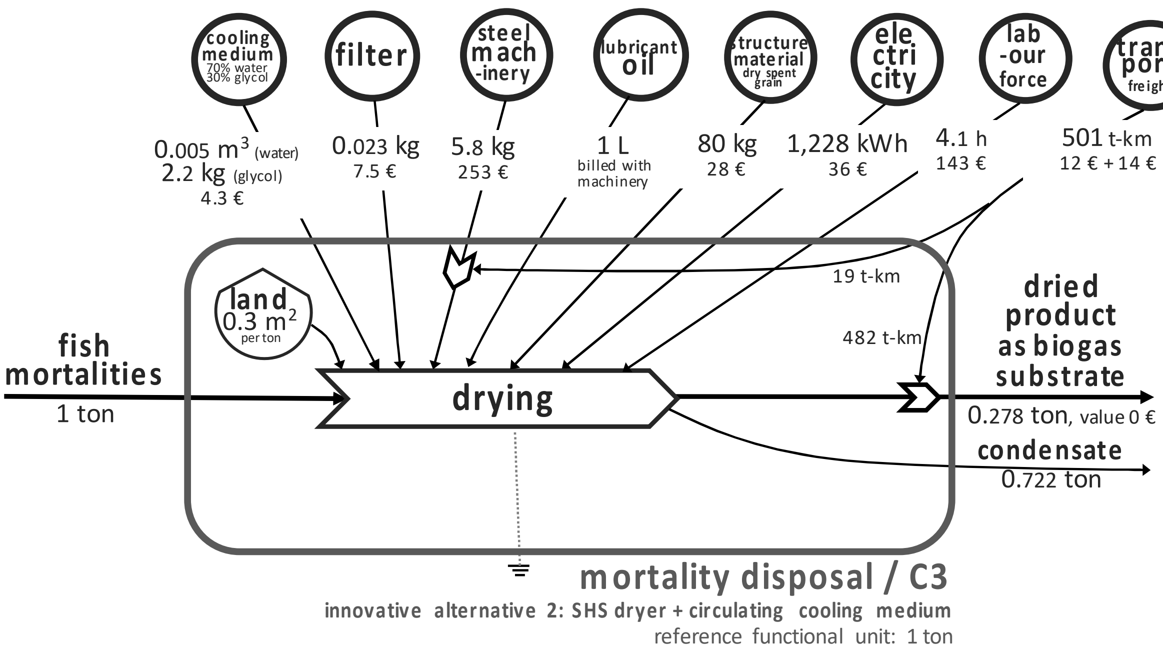


Figure 3.11 – Conceptual and quantitative diagram for fish mortality disposal sub-scenario C3

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

3.2 Scenario-specific accounting choices and assumptions

A reference **functional unit** (FU) of 1 ton was chosen. For each scenario, data were collected, organised, and allocated according to such FU and – where applicable – to the lifetime of the inputs (e.g. machinery).
Annual flows took into account the fact that 18.885 ton of fish mortalities are processed every year in the plant at hand, while steel machinery was computed with a lifetime of 10 years, according to its producers, the plastic tank for the formic acid is replaced every year, and the textile filter is changed three times a year[5].

As far as the **database for modelling** is concerned, the water coming from an adjacent power plant was computed as water for turbine use in Norway, although site-specific, reused water from an industrial plant can potentially represent a common situation for aquaculture by-product processing plants. Directly occupied land was inserted as a sparsely vegetated area. Electricity was elaborated as medium voltage from the Norwegian country mix. Steel machinery is referred to European steel product manufacturing; steel machinery is assumed to be recycled at the end of its life cycle, with a mass-to-mass recycling efficiency of 85% (based on Broadbent, 2016) yielding downgraded low-alloyed steel. Freight transport was modelled based on European lorries with carrying capacities of 3.5-7.5 metric ton and emission category EURO4. Silage tank was computed as a glass fibre object, European production, later disposed of in a landfill as inert waste at the end of its life cycle. The formic acid was processed based on its production in Europe by the methyl formate route; a density of 1.22 kg/L was used for calculations. The plastic tank in which it is delivered was assumed to be made of recycled high-density polyethylene (HDPE) from Europe; at the end of its life cycle, this tank is assumed to be recycled in Europe with a mass-to-mass efficiency of 75% (based on Rigamonti *et al.*, 2009) yielding downgraded granulate amorphous polyethylene terephthalate. The mass of each textile filter is based on a surface mass of 400 g/m^2 (communicated by its producer) and on a squared surface of 60 cm per side (inferred from the technical sheets of the Waister 15 machine); according to its producer's technical sheet, the filter is made of aramidic fibre[6] but, since this textile fibre is not present in the Ecoinvent 3.1 database (Wernet *et al.*, 2016), a viscose textile fibre was chosen (global production); by law, this is incinerated at the end of its life cycle. The structure material, represented by dry spent grains – by-product of beer production – in the eco-innovation at hand, in SimaPro has been computed as bagasse, i.e. the by-product of ethanol production from sweet sorghum (same type of product: end by-product for alcohol production; same vegetable origin: a cereal; general global location); the end of its life cycle depends on the use of the final product from the eco-innovated fish mortality plant: in the basic scenarios B and C, this is computed as general waste, but more specific re-uses (e.g. not-for-human-food animal meal or biogas) might yield different outcomes in the environmental accounting. For lubricant (lubricating) oil, a European production was chosen. After double checking its function and nature, the glycol present in the cooling medium for Scenario 3 was chosen as European liquid propylene glycol; a density of 1.036 kg/L was adopted for calculations.

[5] New data communicated while this deliverable was being concluded suggest the filter may be instead replaced only once a year; however, changes in the LCA model suggest this would not affect the results.
[6] The Waister 15 machine requires a textile filter, which is estimated to be replaced three times a year in a plant annually processing 18,885 ton of fish mortality. This textile filter is realised in aramidic fiber as per a confidential technical sheet issued by the producer on the 10th of February, 2020.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

As to the three **sub-scenarios** related to the end-of-life alternatives for the dried fish mortalities, two elements were considered: transportation inputs and avoided products due to the recirculation into human economies. Regarding the former, mass-distance on-road choices were made with the same choices described above; concerning the latter, yielded savings were accounted for as negative (avoided) inputs. For sub-scenarios 1, the closest animal feed ingredients for pets to be possibly considered as an avoided product were found in fish-based products, present in the category of Animal feed, namely Small pelagic fish, fresh, adjusted for the rest of the world other than Ecuador, and Fishmeal, for the rest of the world other than Peru; 5% in mass of the avoided product was assumed to be represented by the first-quality small pelagic fish, while the other 95% by by-product from anchovy processing. For sub-scenarios 2, the closest item to account for its reuse for energy production in a cement plant was identified as Peat – in the category of Fuels – inasmuch as it is a source of energy composted of organic matter and also containing animal remains; moreover, in the adopted database it is especially available as developed from the inventories by the Nordic Countries Power Association, thus even more relevant for the case study at hand. For sub-scenarios 3, the resource savings due to the final product's reuse as biogas substrate were modelled as avoided Biogas, from grass – in the category of Fuels, subcategory of Biogas – since this is the closest source of biogas coming from similarly dried organic matter; the volume of gas produced out of one ton of dried matter was taken from Martin & Parsapour (2012), dedicating a studio to the same component of the structure material of our case study (brewer's spent grain): 60,000 ton of fresh brewer's spent grain yield 5,880,000 Nm^3 of biogas (*ibid.*); since our case study has dried (not fresh) brewer's spent grain, some adjustments are made based on a 77% water content (after Jackowski *et al.*, 2020), thus adopting a value of 127.3 Nm^3 produced out of each ton of dried product.

3.3 Life-Cycle Impact Assessment (LCIA) results

The results of the LCA-based environmental evaluation of the scenarios for GAIN's eco-innovation are illustrated in **Table 3.1**, divided in two parts, one related to the alternative 1 (SHS dryer and cooling water) and another related to the alternative 2 (SHS dryer and cooling medium). Each part is in turn divided into three sub-scenarios, as per the end-of-life options described above. The rationale behind the indicators and their description has been provided in **Chapter 2**, together with the used methods, as specified in the last column of **Table 3.1**. Percentage data all come from the comparison between the innovative scenarios (B1, B2, B3, C1, C2, and C3) with the reference scenario of ensilage (A). Comparative figures exceeding -100% are due to avoided products, suggesting more-than-compensated impacts.

3.4 Discussion

Almost all the selected LCA indicators show quite significant decreases in the overall environmental impact of fish mortality disposal as a result of the implementation of GAIN's eco-innovations targeting treatment and end-of-life reuse of a current by-product. Most indicators exceed an 80% reduction in the impacts. The Cumulative Exergy Demand shows a net decrease for all (between –76% and –96%), also producing a relative reduction in the use of non-renewable sources and a relative increase in the use of renewable ones. However, one exception ought to be addressed and commented. Scenarios B and C both directly and indirectly require more water – regardless of the end-of-life reuse of the treated product – so environmental gains are reduced: changes in water consumption varies between reduced positive environmental impacts (–13% in sub-scenario B1, –11% in sub-scenario B2, and –8%

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

in sub-scenario B3) and conflicting data (+22%, +26%, and +29% for sub-scenarios C1, C2, and C3, respectively). Water impacts are also indirectly connected to higher electricity consumptions to run the innovative machines, only partially mitigated by the other innovations. Scenario B stands out as the best performing, as the electricity demand is compensated by energy savings in the fish farm linked to the heat contained in the cooling water. *(continues)*

Table 3.1. Life-Cycle Assessment indicators for GAIN's innovations on fish mortality

Part one: innovative alternative 1 (SHS dryer + cooling water, with 3 end-of-life options)

Impact category	Unit	Scenarios				Comparison with A			Met hod
		A	B1	B2	B3	B1	B2	B3	
Global Warming Potential, 100a	kg CO_2 eq	2800	43	91	278	-98%	-97%	-90%	[a]
Stratospheric ozone depletion	kg CFC11 eq	2.E-03	1.E-04	1.E-04	2.E-04	-91%	-92%	-89%	[b]
Terrestrial acidification	kg SO_2 eq	8.6	-1.3	0.3	0.8	-115%	-97%	-91%	[b]
Eutrophication, freshwater	kg P eq	0.424	0.019	0.018	0.038	-95%	-96%	-91%	[b]
Eutrophication, marine	kg N eq	0.031	0.005	0.005	-0.001	-84%	-83%	-104%	[b]
Mineral resource scarcity	kg Cu eq	8.2	0.7	0.4	1.0	-92%	-95%	-88%	[b]
Fossil resource scarcity	kg oil eq	996	12	-30	96	-99%	-103%	-90%	[b]
Water consumption	m^3	28	24	25	26	-15%	-11%	-8%	[b]
Cumulative Exergy Demand	MJ	48728	4088	1923	7750	-92%	-96%	-84%	[c]
Land occupation	m^2 * a	154	13	8	5	-92%	-95%	-97%	[d]
Biochemical Oxygen Demand	kg	8.5	-6.7	0.3	0.7	-179%	-97%	-92%	[d]
Land use	Pt	3.E+04	2.E+03	1.E+03	2.E+03	-92%	-96%	-93%	[e]

Part two: innovative alternative 2 (SHS dryer + cooling medium, with 3 end-of-life options)

Impact category	Unit	Scenarios				Comparison with A			Met hod
		A	C1	C2	C3	C1	C2	C3	
Global Warming Potential, 100a	kg CO_2 eq	2800	71	118	305	-97%	-96%	-89%	[a]
Stratospheric ozone depletion	kg CFC11 eq	2.E-03	2.E-04	2.E-04	3.E-04	-86%	-86%	-84%	[b]
Terrestrial acidification	kg SO_2 eq	8.6	-1.3	0.3	0.8	-115%	-96%	-90%	[b]
Eutrophication, freshwater	kg P eq	0.424	0.029	0.027	0.047	-93%	-94%	-89%	[b]
Eutrophication, marine	kg N eq	0.031	0.006	0.006	-0.001	-81%	-81%	-102%	[b]
Mineral resource scarcity	kg Cu eq	8.2	0.8	0.5	1.1	-90%	-93%	-86%	[b]
Fossil resource scarcity	kg oil eq	996	21	-22	104	-98%	-102%	-90%	[b]
Water consumption	m^3	28	35	36	37	22%	26%	29%	[b]
Cumulative Exergy Demand	MJ	48728	7957	5806	11623	-84%	-88%	-76%	[c]
Land occupation	m^2 * a	154	19	14	11	-88%	-91%	-93%	[d]
Biochemical Oxygen Demand	kg	8.5	-6.3	0.6	1.1	-175%	-92%	-87%	[d]
Land use	Pt	3.E+04	3.E+03	2.E+03	2.E+03	-90%	-94%	-92%	[e]

Method key: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4; [e] Ecological Footprint Method (adapted) V1.00 / Global (2010)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

(continued) Scenario C uses much less water but does not allow for energy savings; furthermore, it uses glycol, also having a higher partial contribution in several indicators, including the ones about water. As to the end-of-life options computed through the three sub-scenarios per innovation, a clear ranking emerges from the environmental indicators: in particular, option 1 performs much better than option 2, and the latter slightly better than option 3. More in detail, the reuse of the dried fish mortality by-product as an ingredient for pet food production allows savings in fishing activities and related transportation. However, these gains might be resized when reuses of other by-products human-oriented food processing are currently present in pet food production. As to the remaining end-of-life options, reuse as direct energy production in a nearby plant performs better than valorisation as biogas substrate in less abundant plants generally requiring longer distances to be travelled from the fish farm.

3.5 Conclusion

Towards generalisation and/or exportation elsewhere, the following ought to be considered:

- in this environmental assessment, a crucial input in the innovative scenarios such as water, albeit coming (and reused) from an adjacent power plant, was entirely allocated to the eco-innovation at hand, so as to avoid underestimating its impact if generalised: in this case, impacts could be only partially allocated to the studied processes, and all indicators – including the problematic ones about water – would decrease; it is therefore important to plan a plant like this quite close to other industrial plants (here, a power plant) that may be available to share their by-products, thus abating the overall environmental impacts;
- scenario B teaches that having a processing plant for fish mortality disposal close to and interconnected with a fish farm allows on the one hand to save resources in the transport before the treatment, and on the other hand to return the heat contained in the cooling water to the farm; this way, valuable electricity can be saved, with different kind of improvements in the environmental indicators based on the current and/or target energy mix in the reference country;
- in both scenarios B and C, a local by-product (here, spent grains) is used as a structure material; in order to keep the benefits, it is important to be in proximity of similar types of plants offering organic waste to be reused, thus saving transport inputs and thus keeping the good performances of the eco-innovations that are here presented and assessed;
- **the best performing eco-innovation is the one that recirculates energy in the fish farm and biomass in another food supply chain (pet food), with a lower use of non-renewable inputs;** although the first feature stands out as the most crucial one, the intuitive benefits coming from the design of a more circular and renewable-based economy look here confirmed.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

4. LCA of GAIN's eco-innovations for sludge valorisation

Based on GAIN's previous deliverables **D2.1** and **D2.5** (Johansen *et al*., 2019; Bruckner *et al.*, 2021) and on technical meetings, the following scenarios were collaboratively designed and progressively double-checked by GAIN partners UNIVE and SHP, as a conceptual basis for the environmental evaluation at hand:

- **scenario A**: a regular smolt RAS (**Figure 4.1**);
- **scenario B**: a RAS equipped with a "S3" filter-dryer, as per D2.1/D2.5 (**Figure 4.2**).

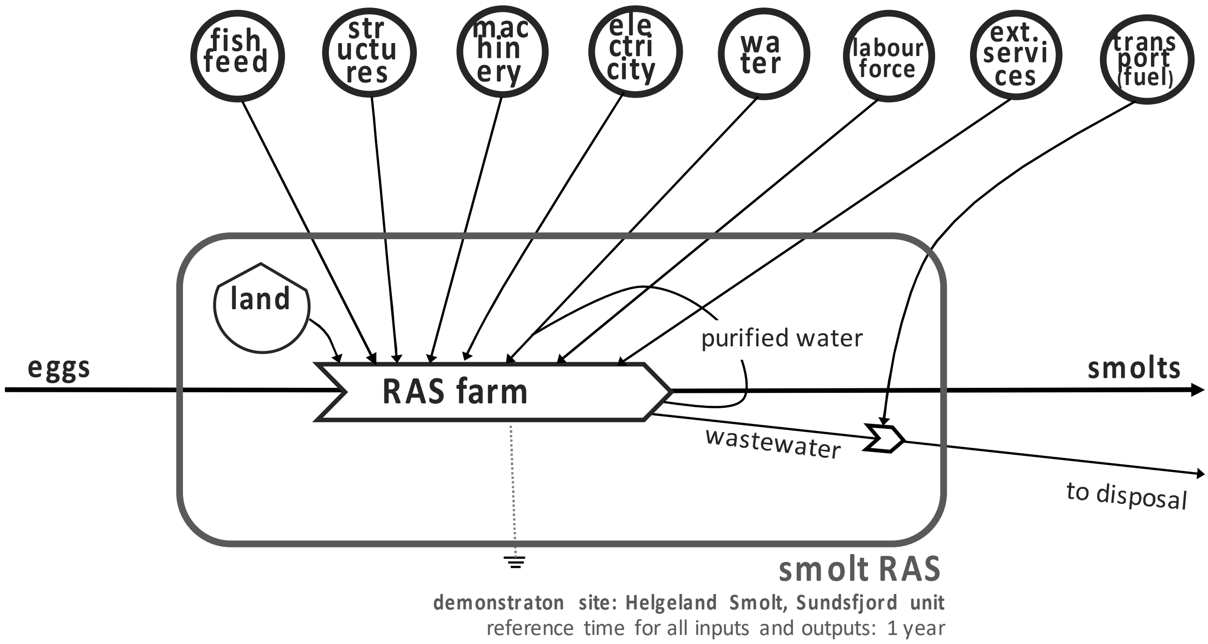


Figure 4.1 – Conceptual qualitative model for sludge valorisation scenario A

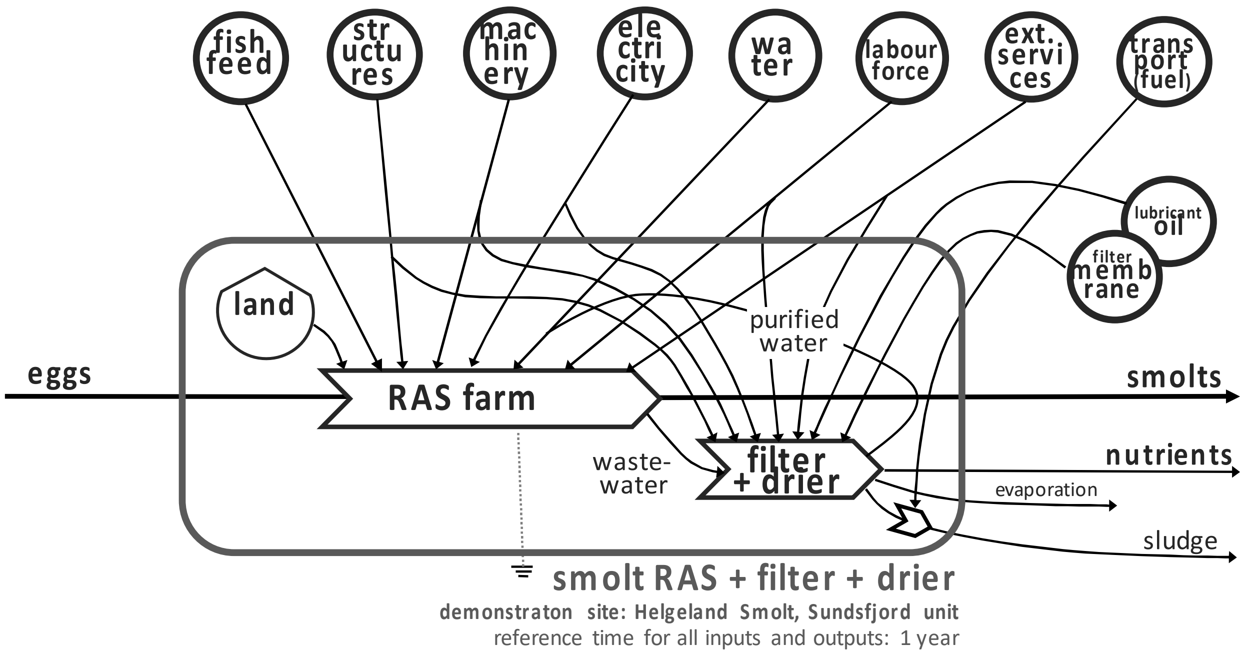


Figure 4.2 – Conceptual qualitative model for for sludge valorisation scenario B

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

A reference **functional unit** (FU) of 1 year of operating system was chosen for the studied plant, corresponding to a smolt production of 1,300 ton.

For each of these scenarios (i.e. regular RAS and its innovation) data were collected, organised, and allocated according to the chosen FU and – where applicable – to the lifetime of the inputs (e.g. machinery). New design by UNIVE and double-check with SHP has led to add quantitative information as per the flow charts below, describing the reference scenario (**Figure 4.5**) and the innovative scenarios (**Figures 4.6–4.8**).

4.1 Main eco-innovations for sludge valorisation tested in GAIN

Recirculating Aquaculture Systems (RAS) are becoming more and more relevant for the salmon industry and its smolt production. A RAS plant is designed to be able to produce large quantities of fish with low water consumption.
In a RAS facility, see **Figure 4.3**, the effluent from fish basins is treated through a mechanical filtration process, in order to remove faeces, waste feed, and other particles. Then, the water goes through a biofilter, which converts ammonium into nitrate. Oxygen is supplied in the gas control unit, where excess CO_2 can also be removed. As a last step, the water is sterilised using UV irradiation before being recirculated to the fish tank. About 1–2% of the water needs to be replaced, to avoid nitrate accumulation.

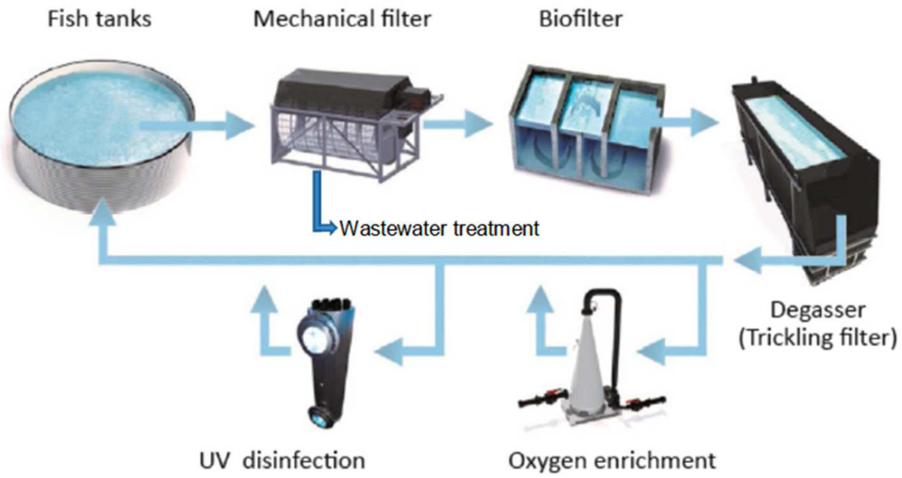


Figure 4.3 – "Principle drawing of a recirculation aquaculture system (RAS). […] (adopted from Bregnballe, 2015)" (D2.1, Figure 1, Johansen *et al.*, 2019)

Compared with the system described above, the Norwegian plant analysed in this chapter includes also a thermal unit for adjusting water temperature.

In a RAS system, a relevant fraction of nutrients is removed from aquaculture wastewaters, including nitrogen and phosphorus. This happens via a mechanical filter (40 and 80 µm mesh size), removing larger particles and producing a nutrient-rich "reject water", which can be further processed. However, a large amount of these substances is still emitted to the sea. By introducing the new S3 filter-dryer system (**Figure 4.4**), Salten Havbrukspark (SHP) aims at significantly reducing the amounts of suspended matter in wastewater streams from aquaculture. Indeed, even though RAS systems make reuse of water from fish production, a

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

large amount of particles and dissolved substances accumulates in the reject water. By developing the new S3 filter-dryer, SHP aims at increasing the amount of particles to be removed from aquaculture wastewater. The S3 filter-dryer uses a filter cloth with a mesh size of 6 µm, removing 93 ± 2.8% of the suspended solids from the reject water. In parallel, resulting sludge is dried by an infrared system minimising the respective energy use for sludge drying and transport.

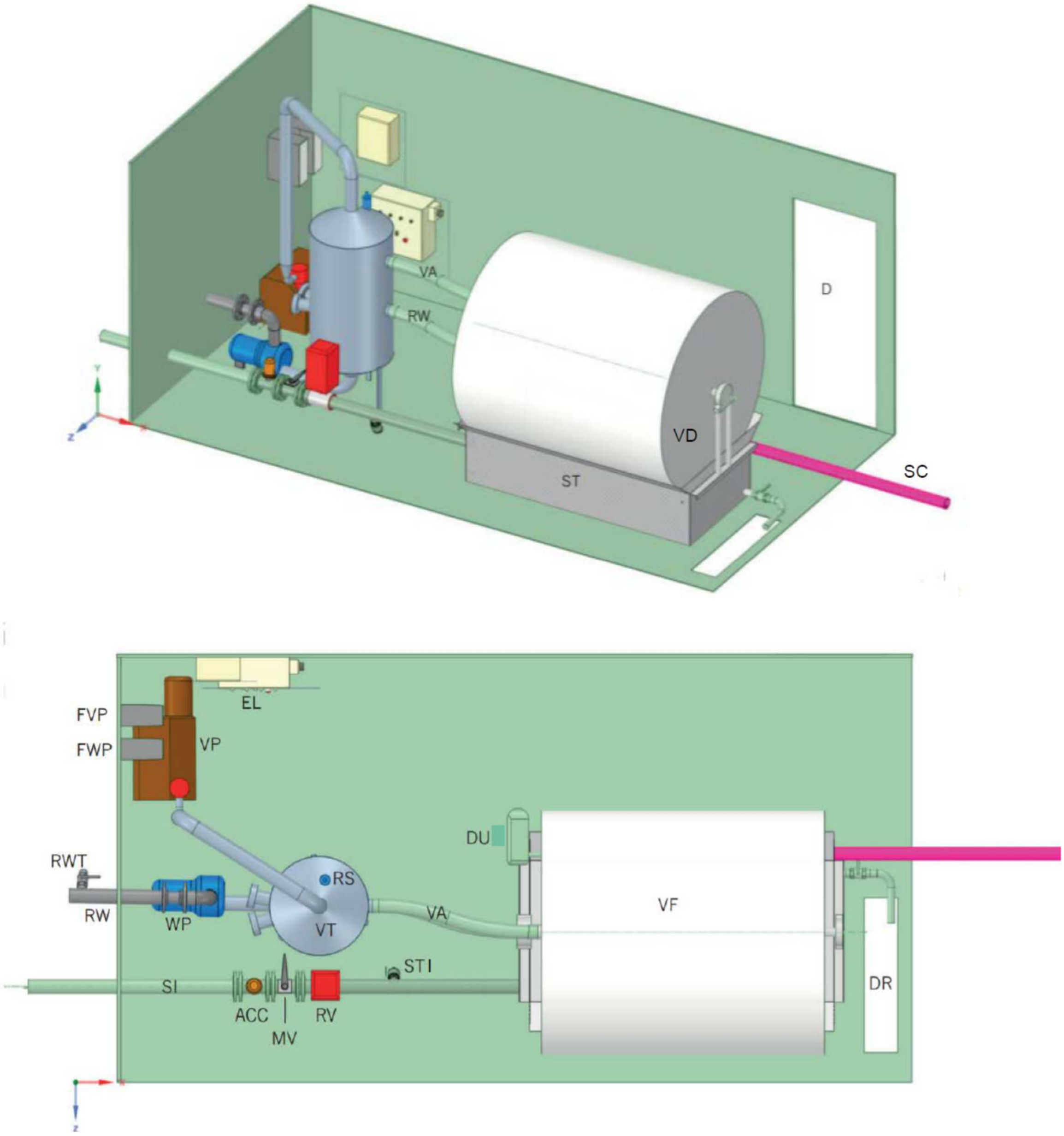


Figure 4.4.a – Overview over the most important components of the S3 filter system[7] (D2.5, Figure 3, Bruckner *et al.*, 2021)

[7] ACC = Activator; BF = Buffer tank; D = Door; DR = Drain; DU = Drive unit; EL = Electrical cabinet; FL = Floor; FVP = Frequence generator vacuum pump; FWP = Frequency generator water pump; KI = Wall; IP = Inlet pipe buffer tank; MV = Manual valve; OF = Overflow pipe; OWV = One-way valve; PP = Pressure clock; PT = Pressure transmitter; RC = Radar sensor; RS = Radar sensor; RV = Regulating valve; RW = Reject water; RWT = Reject water out; SC = Screw conveyor; SI = Sludge in; ST = Sludge tank; STI = Sludge test in; VA = Vacuum air; VB = Vacuum box; VD = Vacuum drum; VF = Vacuum filter; VP = Vacuum pump; VT = Vacuum tank; VV

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Figure 4.4.b – “S3 demonstration unit as produced by LS Optics AB. Right frame shows the details of the filter during change of filter cloth. Photo by Salten Havbrukspark AS (SHP)” (D2.1, Figure 6, Johansen *et al.*, 2019)

For removal of dissolved N and P compounds from aquaculture wastewater (reject water after S3 filtration); seaweed cultivation was also tested, but is not assessed within the present environmental accounting evaluation. The first test by SHP indicates a removal efficiency of more than 96% of suspended organic matter and of more than 30% of total nitrogen. Therefore, the S3 filter system significantly reduces nitrogen emissions due to the discharge of RAS wastewater (reject water). Moreover, particles removed from aquaculture wastewater and dried by the S3 filter may even provide a new nutrient-rich product, to be used as e.g. a fertiliser, as insect feed, etc. Unlike other filtration systems, the S3 filter makes all the wastewater evaporate, and filtration results in a filter cake containing a maximum of 10% water. Evaporation is performed by means of vacuum supported by infrared technology, optimised for highest possible energy efficiency. Other classical filtration systems create a filter sludge, containing often more than 90% water. This wet sludge needs to be dried further, or to be transported wet to a potential customer (using the sludge), to a biogas plant, or to a waste incinerator. The S3 filter-dryer therefore drastically reduces transportation and energy costs for the sludge.

= Vacuum Valve; WP = Water pump. The reject water enriched in particles by a 0.45 µm drum filter is collected in a big reservoir called the buffer tank, holding the liquid waste before it enters the filtering system. The wastewater flows towards the filter drum, a horizontal steel cylinder. Its cylindrical surface is covered by a filter cloth with a mesh size of 6 µm. A vacuum tank is connected to the drum to separate air and liquid discharge from the filter. The whole system is therefore exposed to underpressure, which is used to suck the wastewater through the filter cloth of the immerged filter drum. The vacuum sucks both liquid and solids onto the surface of the filter cloth. The liquid penetrates through the mesh of the cloth while the solids are retained on the drum surface. The drum rotates slowly, which allows the solids to form a filter cake on the drum surface which dries while not in contact with the waste water. The drying process is supported by an infrared unit. The resulting dry sludge is finally scraped off the drum by a knife. This “cleaned” part of the filter cloth then re-enters the waste water and undergoes a new cycle of filter cake build-up/drying/discharge. By using vacuum to draw wastewater through the filter cloth, high flow rates can be achieved, in spite of the fine filter mesh size. The remaining moisture in the dried sludge is actually 6 % – 9 % when it gets discharged from the cloth, depending on waste water characteristics. The resulting sludge product is carried away by a screw conveyor for further processing (Bruckner *et al*., 2021)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

The pilot demonstration site for sludge valorisation corresponds to the one described in section 3.1.1 for fish mortality disposal (the Helgeland smolt plant; specifically, its Sundsfjord unit). The site is located on the coastal part of central Norway (**Figure 4.5**).

Figure 4.5 – Geographical location of the Norwegian district where Johansen *et al.*, 2019)

4.1.1 Main features of innovations for sludge valorisation compared to business-as-usual

Wastewater	Observed values	Analytical method
Suspended solids (>0.45μm) (n=8)	0.006-0.180 %	EN872
- chemical oxygen demand (COD) (n=6)	219-2290 mg/L	EN1899-1
Total phosphorous (n=4)	6.2-9.3 mg/L	ISO6878
Total Nitrogen (n=3)	4.3-7.8 mg/L	ISO15682:2001
Ammonium (n=3)	1.1-6.9 mg/L	ISO11732

Average values for the wastewater leaving a standard RAS system are the following:

- total nitrogen (TN): 0.028 mg/L;
- ammonium (NH_4): 0.036 mg/L;
- Chemical Oxygen Demand (COD): 219 mg/L;
- Suspended Solids (SS): 100 mg/L.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

The S3 filter-dryer unit developed and tested by SHP allows one to deliver purified effluents from aquaculture wastewater with the following features:

- total nitrogen (TN) n=4: 0.23 – 3.1 mg/L; method: ISO15682:2001
- ammonium (NH_4):
- Chemical Oxygen Demand (COD) n=4: <30 mg/L; method: EN1899-1
- Suspended Solids (SS) n=4: < 4 mg/L. method: EN872

Such innovations consist of the following steps:

- removal of particles through S3 filter-dryer;
- drying of particles through S3 filter-dryer;
- seaweed cultivation in particle-free wastewater from aquaculture is possible.

4.1.2 End-of-life product valorisation options

In a similar way compared to what presented and assessed in the previous chapter, three different options are present to valorise the end-of-life product obtained through the GAIN's eco-innovation at hand (Baarset, 2021), addressing the reuse of the dried sludge, which is rich in nutrients. Such options are described right below, and in the present assessment result in smolt RAS's sub-scenarios B1, B2, and B3, as illustrated in **Figures 4.6–4.8**.

<u>Option 1 – Bio-fertiliser product</u>
The dried product leaving the system is used as such as bio-fertiliser. For the Norwegian demonstration plant at issue, this implies transportation by road for nearly 1,000 km.

<u>Option 2 – Bio-energy at cement factory</u>
Dried fish mortalities are used as biomass to produce bio-energy at a cement factory. In our case study, this implies transportation by road for a distance of 351 km.

<u>Option 3 – Biogas substrate</u>
After travelling 534 km by road, the dried output is used as a biomass for gasification and reuse as a secondary energy input in human economies.

As introduced above, options 1, 2, and 3 are respectively illustrated in **Figures from 4.7 to 4.9**. **Figure 4.6**, instead, represents the business-as-usual scenario that SHP's innovation aims at improving (granted that an introduction of a RAS can be seen *per se* as an eco-innovation).

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

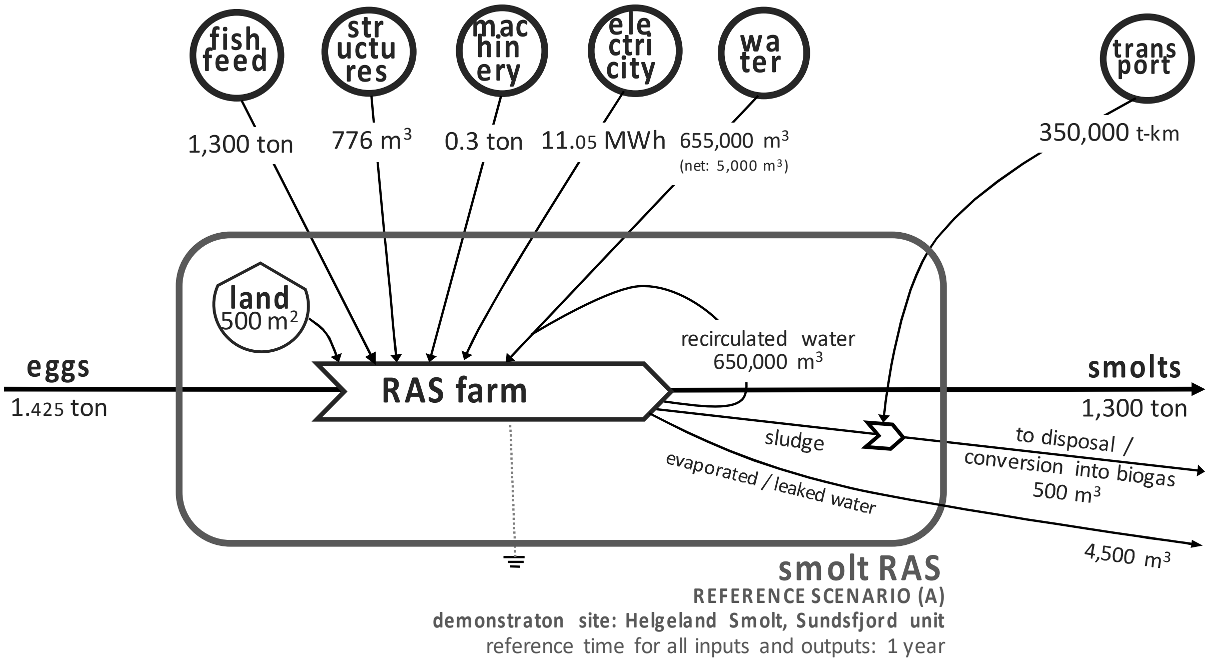


Figure 4.6 – Conceptual and quantitative diagram for sludge disposal scenario A

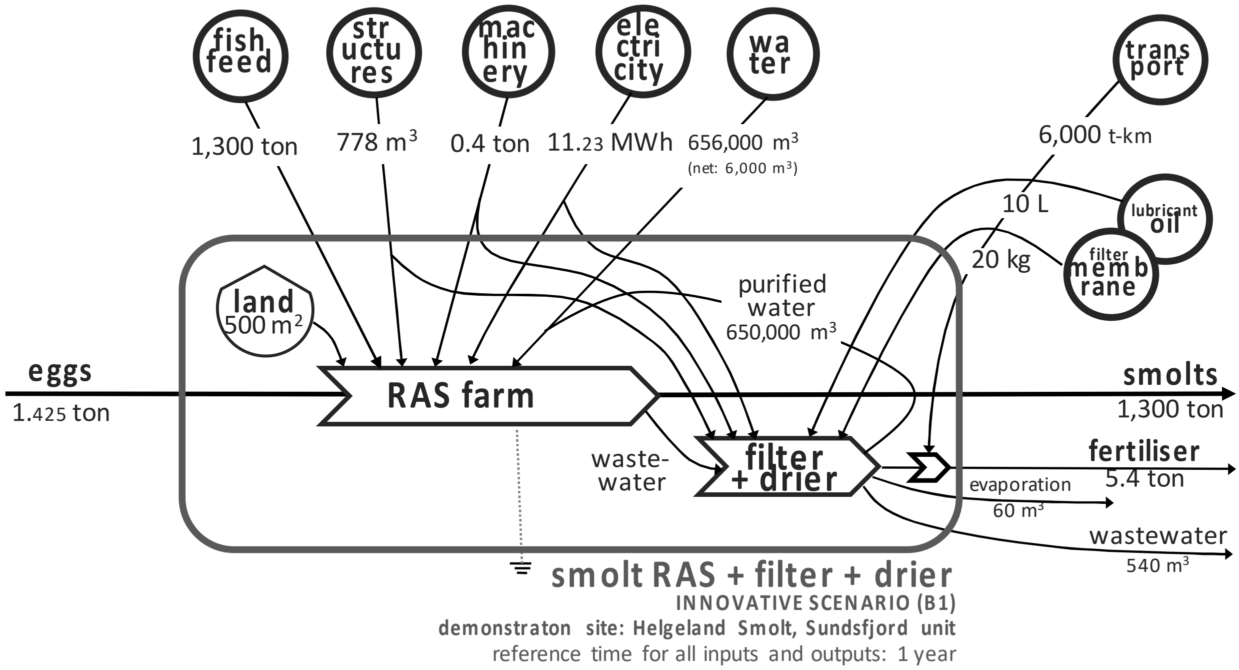


Figure 4.7 – Conceptual and quantitative diagram for sludge valorisation scenario B1

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

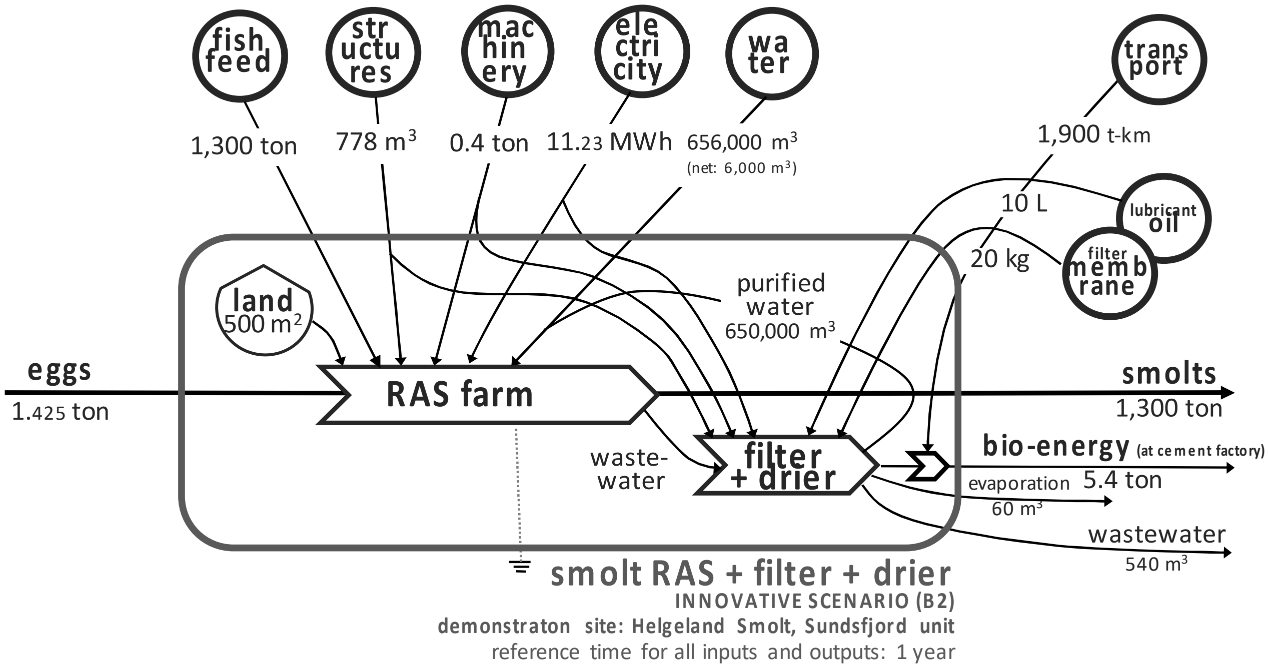


Figure 4.8 – Conceptual and quantitative diagram for sludge valorisation scenario B2

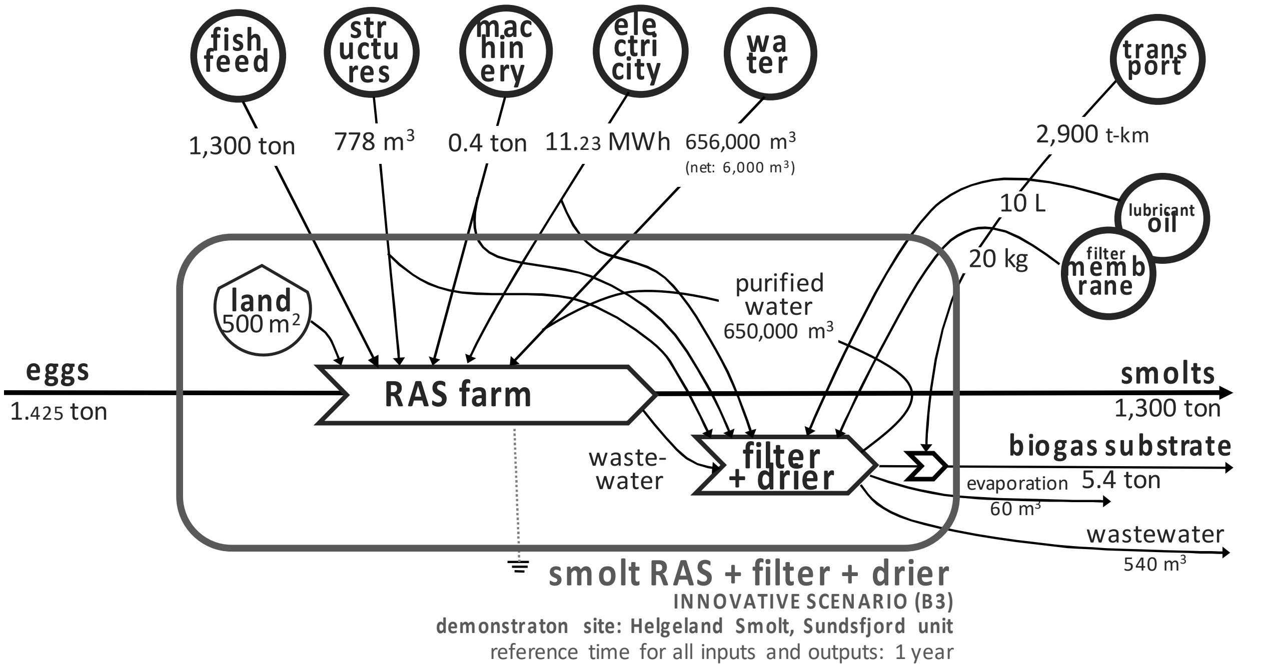


Figure 4.9 – Conceptual and quantitative diagram for sludge valorisation scenario B3

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

4.2 Scenario-specific accounting choices and assumptions

A reference **functional unit** (FU) of 1,300 ton of smolts was chosen[8], i.e. the annual production at the selected plant. Data for Business-as-usual and Innovative scenarios were collected, organised, and allocated according to such FU and – where applicable – to the lifetime of the inputs (e.g. machinery): structures and steel machinery were computed with a lifetime of 20 years, according to their producers and managers. The water coming from industrial pipes and/or rainfall was assumed as water for turbine use in Norway. Directly occupied land was inserted as a sparsely vegetated area, and calculated based on an expected lifetime of 30 years (out of 1.5 ha). Electricity was elaborated as medium voltage from the Norwegian country mix. Steel machinery is referred to European steel product manufacturing; steel machinery is assumed to be recycled at the end of its life cycle, with a mass-to-mass recycling efficiency of 85% (based on Broadbent, 2016) yielding downgraded low-alloyed steel. The RAS structures were considered as a Liquid manure storage and processing facility, including construction, repair, and partial replacement, as a global average plant excluding Switzerland (the item Fish curing plant, including both construction and maintenance, was also present, but it only in terms of plant as a whole, with not enough information about its volumes and materials). Freight transport was modelled based on European lorries with carrying capacities of 3.5-7.5 metric ton and emission category EURO4. For lubricant (lubricating) oil, a European production was chosen for the accounting. Filter membrane, to be replaced annually, was accounted for as high-density polyethylene, recycled, from Europe except for Switzerland, to be disposed of in a sanitary landfill at the end of its life cycle. Fish feed was inserted as Fishmeal, present in the database for all the world except for Peru. For scenario A, end-of-life conversion of undried sludge into biogas is computed as Biogas, treatment of sewage sludge by anaerobic digestion. For sub-scenario B1, bio-fertiliser is accounted for as an item that is present in the category of chemicals, namely, Compost, treatment of bio-waste, industrial composting, average global value excluding Switzerland; indeed, such an item represents nutrients coming from agricultural and food processing by-products. For sub-scenario B2, the closest item to account for its reuse for energy production in a cement plant was identified as Peat – in the category of Fuels – inasmuch as it is a source of energy composted of organic matter and also containing animal waste. Moreover, in the adopted database it is especially available as developed from the inventories by the Nordic Countries Power Association, thus even more relevant for the case study at hand. For sub-scenario B3, the dry matter converted into biogas is computed as a global average value for Biogas, with particular reference to the one coming from the treatment of sewage sludge; nevertheless, since the item in the database exhibits a dry matter of 4–6% (average: 5%) while SHP's innovation is already dried, the equivalent amount of saved biogas is multiplied by 20 in order to account for the correct mass of dry matter, considering an average density equal to that of water (inasmuch as the main component of the process in the database and since the nutrients have similar densities too).

4.3 Life-cycle environmental accounting results

The results of the LCA-based environmental evaluation of the selected scenarios for GAIN's eco-innovation at hand are illustrated in **Table 4.1**, showing the impact categories indicators of SHP's process compared to business-as-usual. The proposal is in turn divided into three sub-scenarios, as per the end-of-life options described above. The rationale behind the indicators

[8] This choice was due to the general variability of the volumes of wastewater to treat depending on multiple internal and external factors but related – indeed – to the same unit of production.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

and their description was provided in **Chapter 2**, together with the used methods, as specified in the last column of **Table 4.1**. Percentage data all come from the comparison between the innovative scenarios (B1, B2, and B3) with the reference scenario without drying (A). Comparative figures exceeding –100% are due to avoided products, suggesting more-than-compensated impacts.

Table 4.1. Life-Cycle Assessment indicators for GAIN's innovation on sludge valorisation

Innovation (Smolt RAS + S3 filter + dryer) with 3 end-of-life options

Impact category	Unit	Scenarios				Comparison with A			Method
		A	B1	B2	B3	B1	B2	B3	
Global Warming Potential, 100a	kg CO_2 eq	1.E+06	9.E+05	9.E+05	9.E+05	-16%	-16%	-16%	[a]
Stratospheric ozone depletion	kg CFC11 eq	5.E-01	4.E-01	4.E-01	4.E-01	-20%	-21%	-21%	[b]
Terrestrial acidification	kg SO_2 eq	9.E+03	9.E+03	9.E+03	9.E+03	-5%	-5%	-5%	[b]
Eutrophication, freshwater	kg P eq	263	244	244	244	-7%	-7%	-7%	[b]
Eutrophication, marine	kg N eq	17.8	16.4	16.4	16.4	-8%	-8%	-8%	[b]
Mineral resource scarcity	kg Cu eq	3860	3350	3340	3350	-13%	-13%	-13%	[b]
Fossil resource scarcity	kg oil eq	3.E+05	2.E+05	2.E+05	2.E+05	-19%	-20%	-20%	[b]
Water consumption	m^3	18600	19100	19100	19100	3%	3%	3%	[b]
Cumulative Exergy Demand	MJ	2E+07	1E+07	1.E+07	1.E+07	-17%	-17%	-17%	[c]
Land occupation	m^2 * a	2.E+05	2.E+05	2.E+05	2.E+05	-3%	-4%	-4%	[d]
Biochemical Oxygen Demand	kg	7.E+04	7.E+04	7.E+04	7.E+04	-1%	-1%	-1%	[d]
Land use	Pt	2.E+07	2.E+07	2.E+07	2.E+07	-8%	-9%	-9%	[e]

Method key: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4; [e] Ecological Footprint Method (adapted) V1.00 / Global (2010)

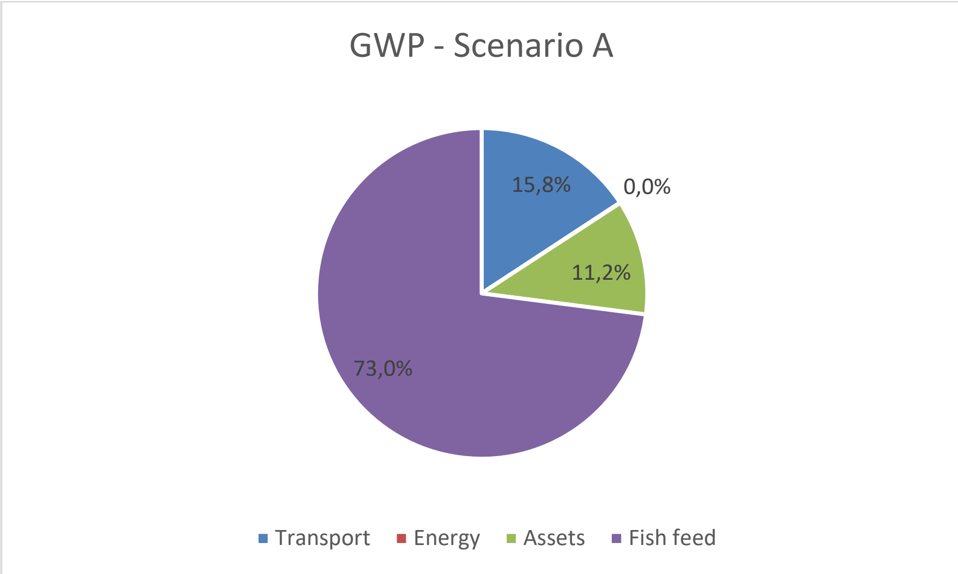
4.4 Discussion

The selected LCA indicators show some decreases in the overall environmental impact that can be associated with sludge valorisation as a result of the implementation of GAIN's eco-innovation targeting wastewater filtration and drying, and end-of-life reuse of the nutrient-rich dried matter as a by-product more valuable than the gasification of sludge as such. Most indicators do not exceed a 20% reduction in the impacts. Compared to reference scenario A, the Global Warming Potential decreases by –16% in all sub-scenarios; the Stratospheric ozone depletion by –20% in sub-scenario B1 and by –21% in the other two sub-scenarios; Mineral resource scarcity and Cumulative Exergy Demand are respectively reduced by –13% and –17% regardless of the end-of-life option; Fossil resource scarcity is also reduced by nearly –20%. The remaining impact category indicators undergo smaller reductions (–1% up to –9%), with the sole exception of Water consumption, slightly increasing by +3% as a consequence of the innovative scenario.

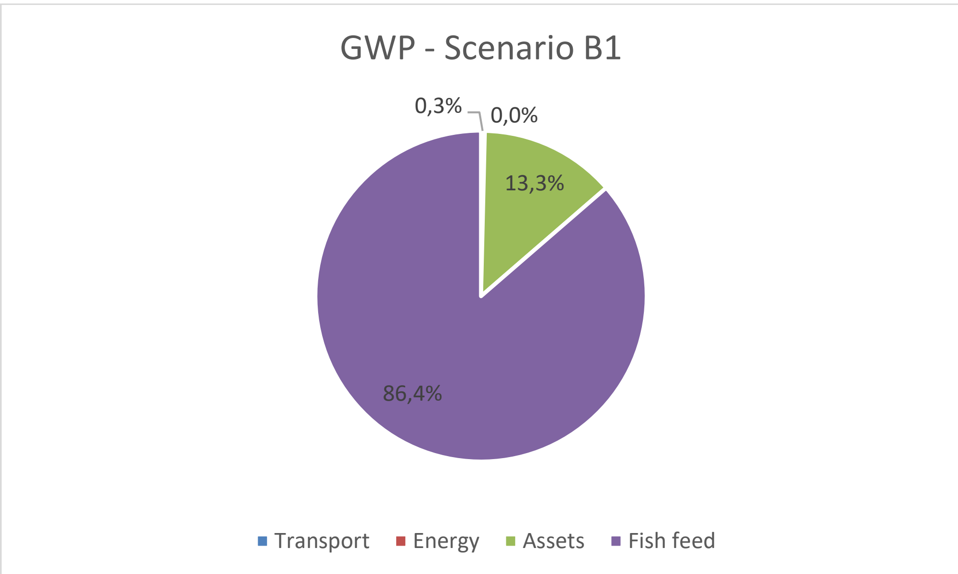
However, input water is greater than +20%, while the overall demand at the end of the environmental assessment is +3%; this suggests that some improvements are still present in the innovative scenarios, with further margins mostly related to the actual input. As to the other indicators, one remark ought to be done. Apart from Mineral resource scarcity (nearly 60%) and Water consumption (nearly 15%), stable in both reference and innovative scenarios, the relative contribution to each impact category indicator suffers from the prominence of one item; in particular, a bias is represented by the imported good "Fish feed", always responsible of more than 80% in all of the remaining figures in sub-scenarios B1, B2, and B3

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

(in **Figures 4.10.a–4.10.d**, relative contributions to GWP highlight the role of fish feed), sometimes reaching 99.6% as in the case of Biochemical Oxygen Demand; however, as noted for Water consumption, this proportion increases compared to scenario A, while the other relative contributions decrease, thus showing net environmental savings that can be associated with the innovation at hand, although dwarfed by the only fixed input that is common to all scenarios, i.e. the not negligible fish feed, matched to production and still only marginally relevant (but surely required) for the environmental assessment of GAIN's innovations.

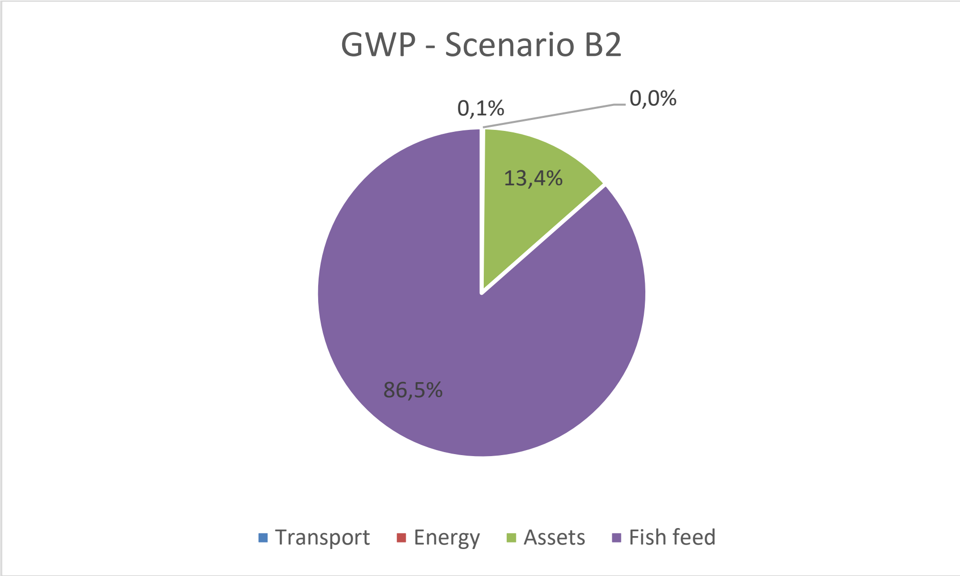


(a)

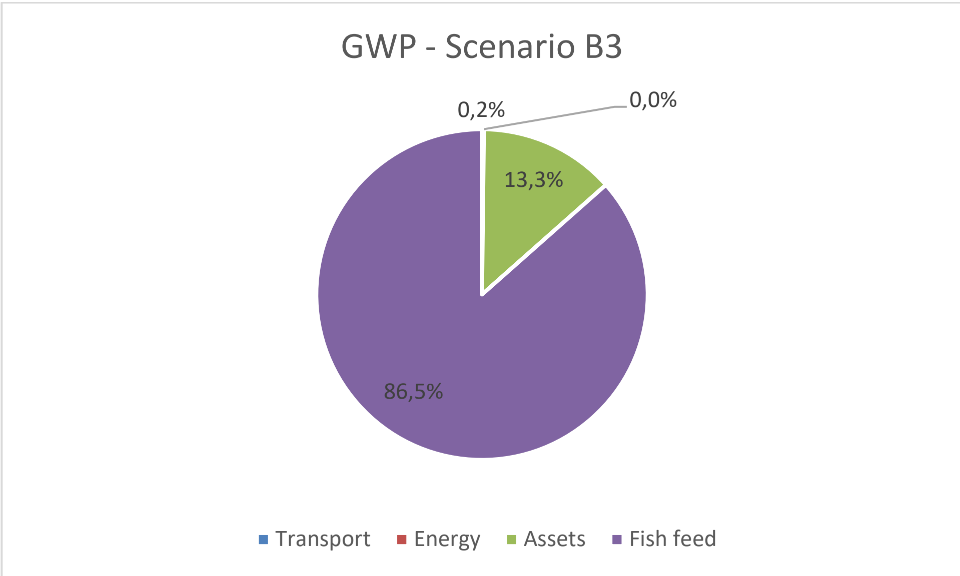


(b)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330



(c)



(d)

Figures 4.10.a,b,c,d – Fish feed is a major input common to all scenarios, and biases the results

In the light of the distorsions caused by fish feed, the assessment was repeated by removing this major input, which is after all common to all scenarios. New results without fish feed are shown **in Table 4.2**. There, percentage variations are amplified compared to **Table 1**; this is valid for the increase in water consumptions (now reaching +7%), but also for all the other inputs, suggesting decreases in the rest of selected environmental impacts ranging from –16% (Mineral resource scarcity) up to –67% (Stratospheric ozone depletion).

Unlike the innovations about fish mortalities, presented in the previous **Chapter 3**, this time there is no emerging end-of-life sub-scenario; it seems this is not due to the distorsions of fish feed (**Table 1**), since results are comparable also in **Table 2**.

GAIN's innovations for RAS sludge valorisation generally perform very well. At the same time, the present assessment confirms a frequent trend according to which fish feed represents a major input when it comes to the environmental impact of aquaculture.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table 4.2. Life-Cycle Assessment indicators for GAIN's innovation on sludge valorisation, excluding the fish feed input

Innovation (Smolt RAS + S3 filter + dryer) with 3 end-of-life options

Impact category	Unit	Scenarios				Comparison with A			Method
		A	B1	B2	B3	B1	B2	B3	
Global Warming Potential, 100a	kg CO_2 eq	3.E+05	1.E+05	1.E+05	1.E+05	-57%	-58%	-58%	[a]
Stratospheric ozone depletion	kg CFC11 eq	1.E-01	5.E-02	5.E-02	5.E-02	-67%	-67%	-67%	[b]
Terrestrial acidification	kg SO_2 eq	9.E+02	4.E+02	4.E+02	4.E+02	-56%	-57%	-57%	[b]
Eutrophication, freshwater	kg P eq	58	4.E+01	4.E+01	4.E+01	-33%	-33%	-33%	[b]
Eutrophication, marine	kg N eq	3.5	2.E+00	2.E+00	2.E+00	-41%	-42%	-42%	[b]
Mineral resource scarcity	kg Cu eq	3,277	3.E+03	3.E+03	3.E+03	-16%	-16%	-16%	[b]
Fossil resource scarcity	kg oil eq	9.E+04	3.E+04	3.E+04	3.E+04	-68%	-69%	-69%	[b]
Water consumption	m^3	7,421	8.E+03	8.E+03	8.E+03	7%	7%	7%	[b]
Cumulative Exergy Demand	MJ	5.E+06	2.E+06	2.E+06	2.E+06	-58%	-60%	-59%	[c]
Land occupation	$m^2 * a$	3.E+04	2.E+04	2.E+04	2.E+04	-23%	-24%	-24%	[d]
Biochemical Oxygen Demand	kg	8.E+02	3.E+02	3.E+02	3.E+02	-64%	-64%	-64%	[d]
Land use	Pt	6.E+06	3.E+06	3.E+06	3.E+06	-44%	-45%	-45%	[e]

Method key: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4; [e] Ecological Footprint Method (adapted) V1.00 / Global (2010)

4.5 Conclusion

Towards generalisation and/or exportation elsewhere, the following ought to be considered:

- in this environmental assessment, savings emerge after the eco-innovation proposed within GAIN, ranging from –16% up to –67% when fish feed is excluded;
- GAIN innovations do not account for fish feed, common to all scenarios; feed is here confirmed as a major contributor to the environmental impact of fish farming, thus potentially able to resize the good performances of the innovations at hand if accounted altogether;
- a slight increase is present regarding Water consumption, linked to a larger input, but such increase is reduced thanks to efficiency of the rest of the innovation;
- the three end-of-life options seem to perform similarly, so no markedly better alternative emerges in the environmental impact categories that were here calculated.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

5. LCA of GAIN's eco-innovations for RAS biofilter fillers

The eco-innovations about biofilters consist in reusing mussel shells to replace plastic rings in RAS with biofilters, as outlined in GAIN's deliverables **D2.4** (Sousa *et al.*, 2019) and **D2.8** (Regueiro *et al.*, 2021). In particular, shells from Spanish cannery industries on the Atlantic coasts were tested, at a lab scale (TRL 4-5). Three containers were used, whose capacity is 10 L each: two of them were filled with shells (whole and crushed, respectively) and one with plastic rings. The filter filled with plastic rings represents the business-as-usual scenario, and the biofilters filled with whole and crushed shells represent instead the eco-innovations within GAIN. It might be worth to recall here that the main aim of all of these filters is wastewater nitrification. Therefore, three scenarios were designed, in collaboration with UNIVE, as a conceptual basis for the Life-Cycle environmental evaluation:

- **scenario A**: filter with plastic rings, business-as-usual, lab scale;
- **scenario B**: filter with crushed shells, innovation, lab scale;
- **scenario C**: filter with whole shells, innovation lab scale.

An additional scenario was also considered, based on scaling-up of scenario C:

- **scenario D**: filter with whole shells, pilot plant scale.

For the environmental assessment at hand, ANFACO shared some further data with UNIVE in addition to the information contained in the appropriate project deliverable, as cited above. This allowed for a more suitable qualitative and later quantitative definition of such scenarios A through to D, compatibly with the expected TRL of the biofilter innovation within GAIN (which is lower than the eco-innovations presented above).

A reference **functional unit** (FU) of 300 L of wastewater to filter/purify was chosen for the lab scale scenarios. This FU corresponds to a time boundary of one month of experiments at a lab scale and to one day of operation at the pilot scale. For lab-scale scenarios, average values of inputs were chosen since longer tests were performed by ANFACO. For each scenario, data were collected, organised, and allocated according to the chosen FU and – where applicable – to the lifetime of the inputs (e.g. machinery). New design by UNIVE and double-check with ANFACO led to add quantitative information as per the flow charts that are reported below, describing the reference scenario at lab scale (**Figure 5.3**), the innovative scenarios at lab scale (**Figures 5.4–5.5**), and the innovative scenario at pilot plant scale (**Figure 5.6**).

A typical RAS is represented in **Figure 5.1**, cited from deliverable **D2.4** (Sousa *et al.*, 2019). Nitrification is a key step, in which, ammonium, which is toxic for fish at low concentrations, is removed in the biofilter. The latter can be used also for removing excess nitrate, in order to reduce water renewal rate. The structure of a biofilter is shown in **Figure 5.2.** It currently consists in plastic rings or spheres, thus posing an environmental issue in both their production processes and in their end-of-life disposal. Also, plastic filter media require the use of sodium hydrogen carbonate ($NHCO_3$) for controlling pH.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

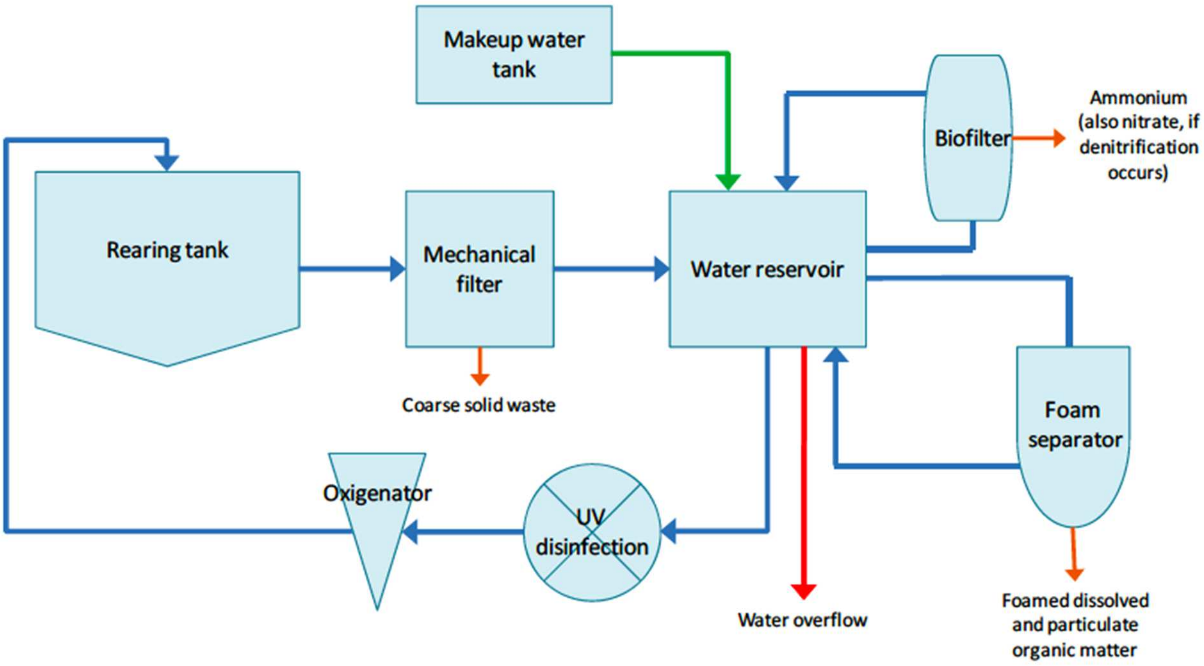


Figure 5.1 – “Simplified schematic design of a typical RAS, showing the most important elements of water fluxes and treatment. Blue arrows: recirculated water; green arrow: clean makeup water inlet; red arrows: used recirculated” (Figure 1 in D2.4, Sousa *et al.*, 2019)

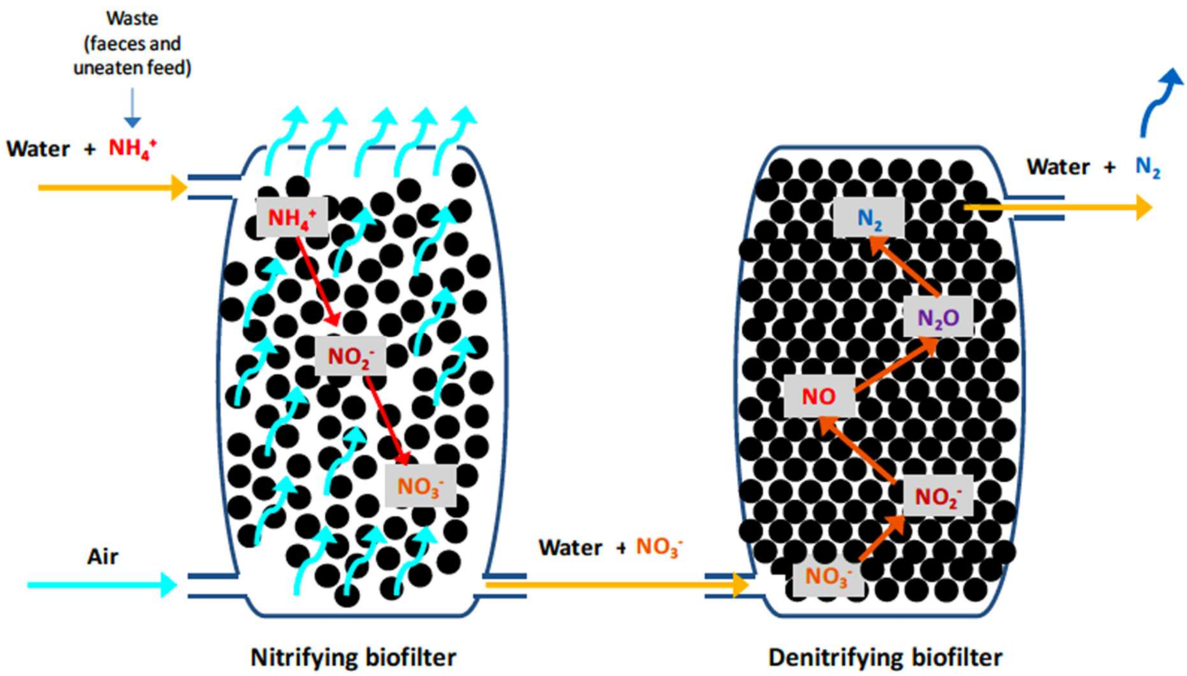


Figure 5.2 – “Schematic diagram of nitrifying and denitrifying biofilters, showing water and air fluxes and the intermediate and final products of nitrification and denitrification. Left: in nitrifying biofilters, air is injected to supply oxygen, thus keeping particles in suspension (fluidized bed reactor). Bacteria oxidize ammonium to nitrate, which tends to accumulate. Right, the denitrifying biofilter is a packed bed reactor where the absence of aeration and the low water exchange help to maintain an anoxic environment that enables the reduction of nitrate to elemental nitrogen, which is finally released to the atmosphere” (Figure 2 in D2.4, Sousa *et al.*, 2019)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

5.1 Main eco-innovations for wastewater nitrification in RAS filter within GAIN

The eco-innovations invetigated by ANFACO consists in substituting plastic rings with bivalve mollusc shells as biofilter filler: high quantities of shells must be disposed every year (in Spain, almost 300,000 ton of mussels are produced every year, Iribarren *et al.*, 2010) by the cannery industry and are currently valorised to obtain calcium carbonate (Barros *et al.*, 2009). Therefore, the reuse of shells in RAS could represent an interesting way of valorising a high amount of biomass which is currently treated as a waste, in the very spirit of a more circular economy. At the lab scale, whole and crushed shells were used, while whole shells only were used at the pilot plant scale. Lab tests were conducted by ANFACO with seawater, while the pilot scale system was operated with an effluent from a trout plant (i.e. freshwater), adding ammonium acetate to simulate high nitrogen loads. The biofilter was re-designed in order to fit in whole and crushed mussel shells instead. Regarding the effluent characteristics, 5 ppm N-NH_4^+ were applied as initial concentration, based on 4–7 ppm N-NH_4^+ data coming form real plants (Tossavainen *et al.*, 2019). With such features, in the time frame at hand (i.e. one day; Regueiro *et al.*, 2021), the following results were reached:
- in seawater (only nitrification), biofilters were able to eliminate all ammonium and all nitrite;
- in freshwater (both nitrification and denitrification steps): almost 100% of ammonia, nitrite and nitrate removal yields.

Building on the results that have just been illustrated in GAIN's project deliverable **D2.4** (Sousa *et al.*, 2019), and as confirmed in further communications by ANFACO, performances seem comparable in all scenarios, thus allowing for easier environmental assessments of the different impacts of different inputs related to the same FU and yielding comparable performances.

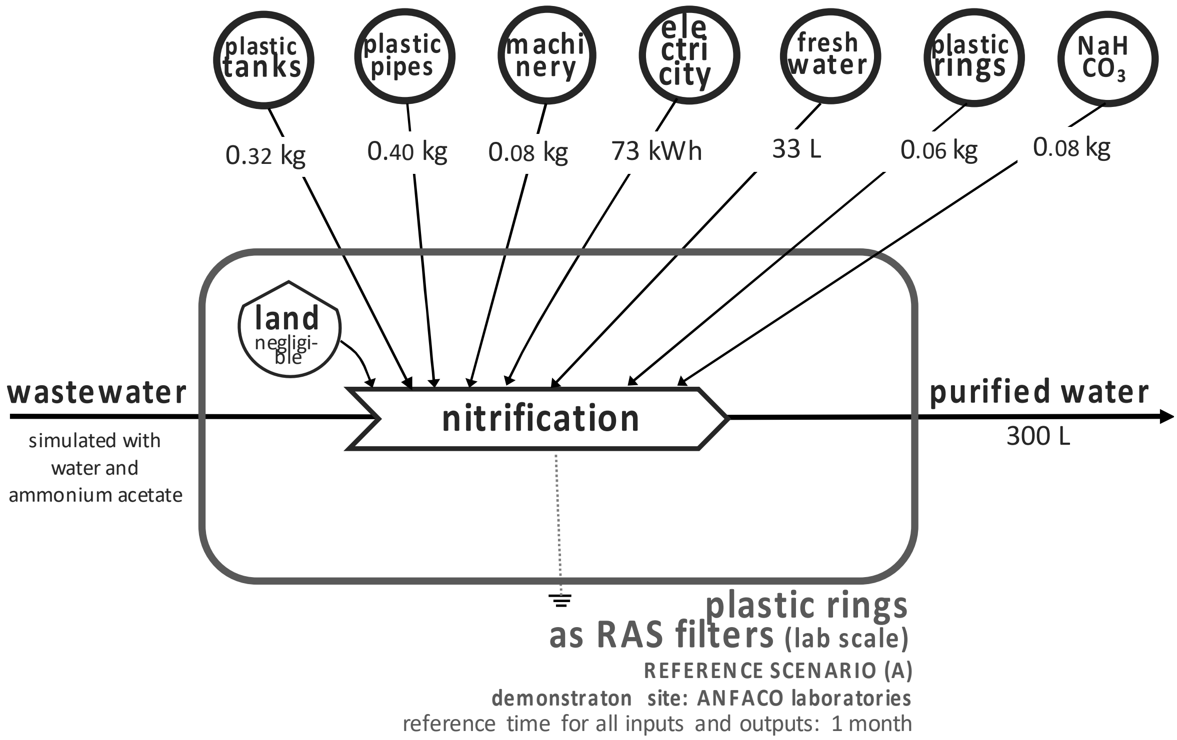


Figure 5.3 – Conceptual and quantitative diagram for filter scenario A

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

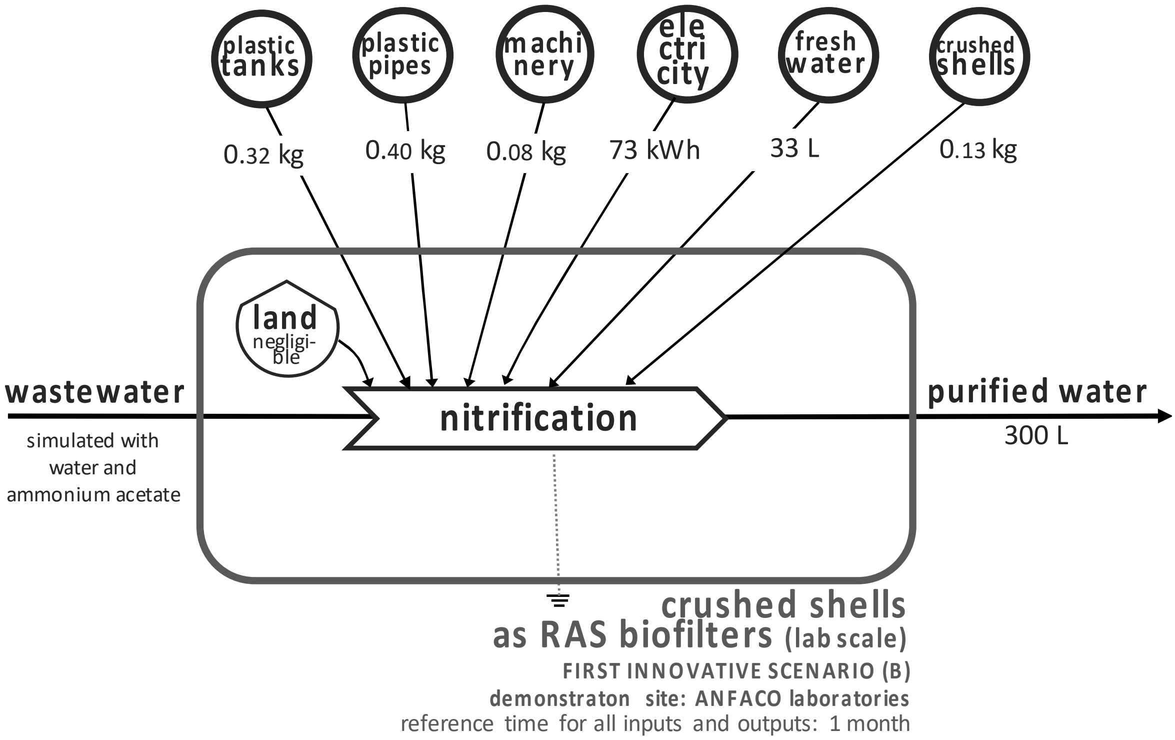


Figure 5.4 – Conceptual and quantitative diagram for filter scenario B

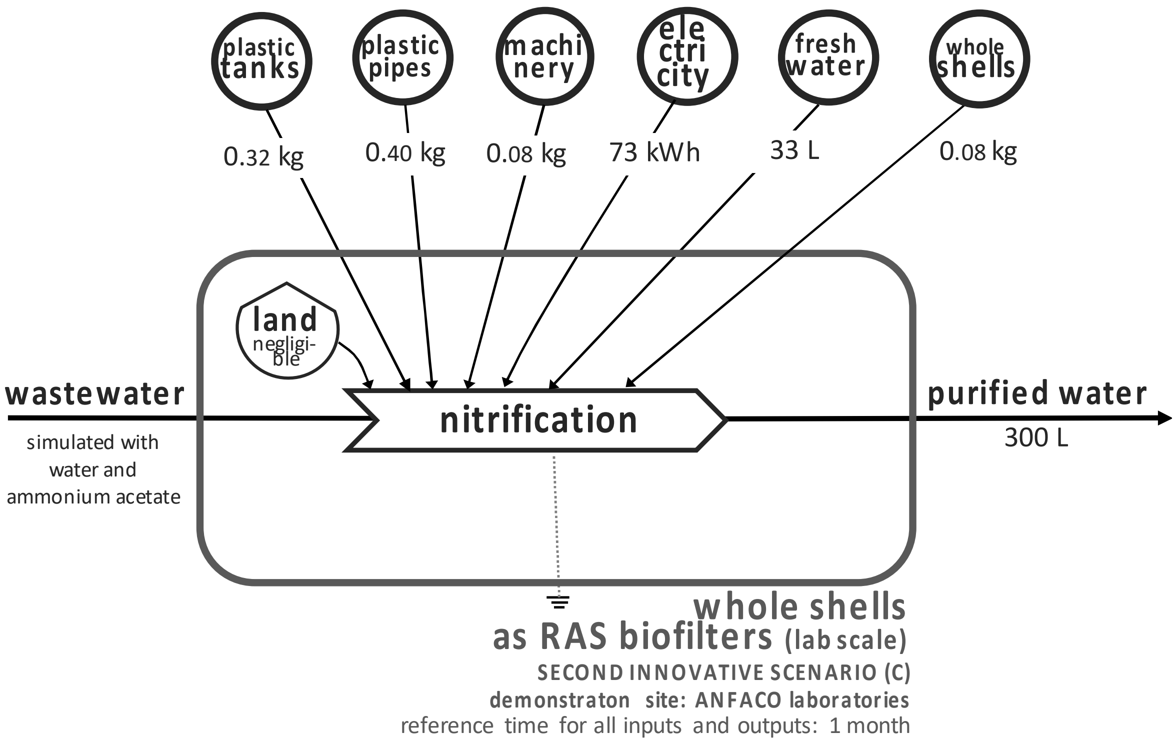


Figure 5.5 – Conceptual and quantitative diagram for filter scenario C

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

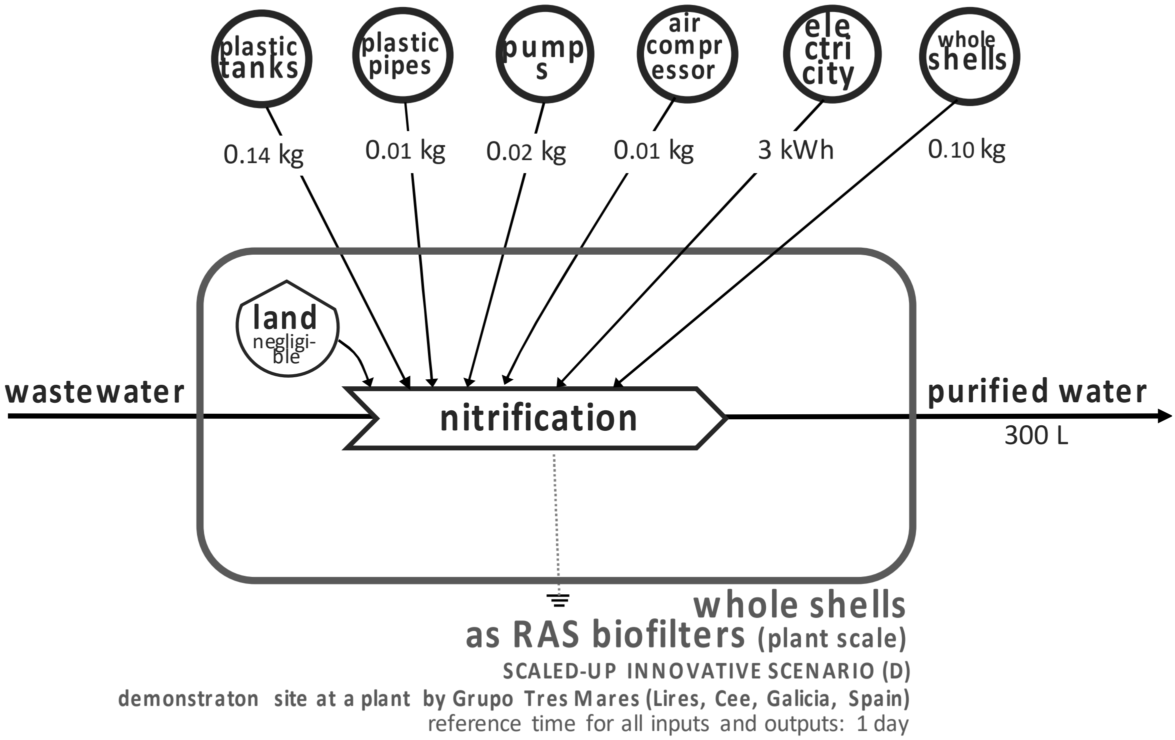


Figure 5.6 – Conceptual and quantitative diagram for filter scenario D

For both reference and innovative scenarios at the lab scale, biofilters were tested with a volume of 10 L, built in methacrylate, with 3 different parts, separated by a mesh that retains the packaging material; these prototypes (**Figure 5.7**) are cheap, occupy as much space as an office desk, and after several months working no solids accumulation was detected.

The pilot scale system was operated inside a real plant (by Grupo Tres Mares, Lires, Cee, Galicia, Spain); this system is composed of 2 biofilters integrated in a pilot plant with nitrification and denitrification steps included with a volume of 300 L. ANFACO was able to work at a HRT of 1 day (i.e treating 300 L/day) with 5 ppm of N-NH_4.

Figure 5.7 – "Built biofilter prototypes. Aeration is provided through an inlet at the bottom connected to an airstone" (Figure 4 in D2.4, Sousa *et al.*, 2019)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

5.2 Scenario-specific accounting choices

A reference **functional unit** (FU) of 300 L of purified wastewater was chosen, i.e. the monthly amount that could be treated at ANFACO's lab scale and their reference unit used at the pilot scale.For each of the above described four scenarios, data for Business-as-usual and Innovative scenarios were collected, organised, and allocated according to such FU and – where applicable – to the lifetime of the inputs: pipes and machinery were computed with a lifetime of 20 years, according to their producers and managers.

The water was computed as water, unspecified natural origin, in Spain. Directly occupied land neglected since lab-scale tests occupy office space as large as <<1 m^2 and anyway already used for other activities, and since pilot-plant-scale require also very little and anyway no additional space in a RAS. Electricity was elaborated as medium voltage from the Spanish country mix. General steel machinery is referred to European steel product manufacturing; steel machinery is assumed to be recycled at the end of its life cycle, with a mass-to-mass recycling efficiency of 85% (based on Broadbent, 2016) yielding downgraded low-alloyed steel. Considering that pumps and air compressors are only available in product units in the adopted inventory, thus exhibiting a margin of uncertainty related to their actual mass, and that quantities are extremely small in all scenarios (especially compared with other inputs, e.g. the plastic ones), pumps and air compressors were computed as steel machinery too, so as to obtain more accuracy in the definition of their quantities. In scenario A, plastic rings were computed as follows: since 100% their K1 material is mostly imported virgin high-density polyethylene (HDPE) from China, virgin high-density polyethylene from the rest of the world other than Switzerland and Europe was chosen; a 10% loss for ring production was assumed compared to HDPE thermoplasts, and end-of-life treatment was defined as sanitary waste due to their content of residues from wastewater mostly preventing other uses in European countries; sanitary waste was assigned polyethylene and sludge material types, respectively. In scenarios B–D, mussel shells were analyses as fish residues, global average value. Plastic pipes were elaborated as European average polyvinylchloride, bulk polymerised, to be recycled at the end of its life-cycle, producing more polypropylene with a mass-to-mass efficiency of 75% (based on Rigamonti *et al.*, 2009). The plastic tanks were assumed to be made of recycled high-density polyethylene (HDPE) from Europe; at the end of its life cycle, these tanks are assumed to be recycled in Europe with a mass-to-mass efficiency of 75% (based on Rigamonti *et al.*, 2009), downgraded into granulate amorphous polyethylene terephthalate. Finally, sodium hydrogen carbonate ($NHCO_3$), for scenario A only, was modelled exactly as sodium bicarbonate, soda production, Solvay process, in Europe; its end-of-life was associated with the treatment of residues from cooling tower, i.e. wastewater with high concentration of nitrogen and calcium.

5.3 Life-cycle environmental accounting results

The results of the LCA-based environmental evaluation of the selected scenarios for GAIN's eco-innovation at hand are illustrated in **Table 5.1**, showing the impact categories indicators of ANFACO's prototype (innovative filler in biofilter) compared to business-as-usual. Three filler media sub-scenarios were modelled: lab scale with crushed (B) and whole (C) mussel shells, and pilot project (plant) scale (D) with whole mussel shells. The rationale behind the indicators and their description has been provided in **Chapter 2**, together with the used methods, as specified in the last column of **Table 5.1**. Percentage data come from the comparison between the innovative scenarios at a lab scale (B and C) with the reference

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

scenario at a lab scale (A), using plastic rings as biofilters. No comparison was possible for the pilot project scale scenario (D), since no business-as-usual scenario was modelled as the test of ANFACO innovation at a higher TRL was not originally planned in GAIN. However, some interesting hints emerge in the light of the scaling up of the innovation.

Table 5.1. Life-Cycle Assessment indicators for GAIN's innovation on RAS biofilters

Innovative alternative with mussel shells (whole + crushed at lab scale, whole at plant scale)

Impact category	Unit	Scenarios				Comparison with A		Method
		A	B	C	D	B	C	
Global Warming Potential, 100a	kg CO_2 eq	25.6	25.4	25.4	0.9	-1%	-1%	[a]
Stratospheric ozone depletion	kg CFC11 eq	2.E-05	2.E-05	2.E-05	8.E-07	0%	0%	[b]
Terrestrial acidification	kg SO_2 eq	0.16	0.16	0.16	0.01	-1%	-1%	[b]
Eutrophication, freshwater	kg P eq	1.E-02	1.E-02	1.E-02	4.E-04	0%	0%	[b]
Eutrophication, marine	kg N eq	1.E-03	1.E-03	1.E-03	1.E-04	4%	1%	[b]
Mineral resource scarcity	kg Cu eq	4.E-02	3.E-02	3.E-02	2.E-03	-2%	-2%	[b]
Fossil resource scarcity	kg oil eq	6.9	6.8	6.8	0.2	-2%	-2%	[b]
Water consumption	m^3	0.359	0.355	0.355	0.010	-1%	-1%	[b]
Cumulative Exergy Demand	MJ	734	728	728	31	-1%	-1%	[c]
Land occupation	$m^2 * a$	2.3	2.2	2.2	0.1	-1%	-1%	[d]
Biochemical Oxygen Demand	kg	2.E-02	2.E-02	2.E-02	6.E-03	11%	11%	[d]
Land use	Pt	185	183	183	8	-1%	-1%	[e]

Method key: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4; [e] Ecological Footprint Method (adapted) V1.00 / Global (2010)

5.4 Discussion

The selected LCA indicators show some very small variations in the overall environmental impact that can be associated with biofilters as a result of the implementation of GAIN's eco-innovation targeting the used filling materials. Smaller masses of virgin high quality plastics (HDPE) and sodium bicarbonate versus larger masses of some former waste to be re-circulated, i.e. mussel shells from the regional cannery industry. The relative environmental impacts that can be associated with such biofilters tend not to exceed 1% in most impact categories. As a result, gains and detriments are quite limited. A general trend from 0% to –2% can be registered due to avoided plastics, reaching the –2% exactly in the category of fossil fuel scarcity, linked to saved oil as a raw material. There is basically no difference between scenario B and scenario C, inasmuch as they exhibit almost the same inputs, except for different masses of crushed (0.13 kg) and whole (0.08 kg) mussel shells, respectively. It is right such a feature that lies behind the only diverging impact category. As a matter of fact, marine eutrophication is higher in scenario B, associated with a larger amount of shells compared with scenario C; furthermore, such an indicator is also higher in these eco-innovative scenarios when compared with the reference one. This can be explained with the fact that, although representing a valuable resource coming re-circulated waste, shell-based biofilters become by law hazardous waste after they act as filters in a RAS, thus their "natural" origin does not ley anyone return the shells to the ecosystems, but they are rather prescribed to be disposed of

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

safely in a sanitary landfill; this is the same end-of-life destination of plastic rings, but their mass is smaller, thus yielding a smaller environmental impact in such a category and even more clearly in the other category of biochemical oxygen demand, also connected to the "past" life of yet a re-circulated resource. Results at the pilot project scale suggest positive effects deriving from the scaling up of the eco-innovation, which is anyway out of the scopes of GAIN's activities.

5.5 Conclusion

Towards generalisation and/or application elsewhere, the following ought to be considered:

- the replacement of plastic rings with waste mussel shells as filling materials for biofilters allows for the saving of fossil fuels and implies some gains in most of the selected impact categories; in any case, however, the impacts related to the filling materials are two orders of magnitude lower than the overall impacts connected to a biofilter's operations in a RAS, thus environmental gains are quite limited;
- two typically ecological impact categories (i.e. marine eutrophication and biochemical oxygen demand) suffer from the fact that, in the light of their filtration activity, biofilter filling materials are all meant to become hazardous materials at the end of their life cycles, so the differences between chemically synthesised plastics and re-used organic materials from other aquaculture sectors is flattened; what is more, larger masses of shells are required compared with plastic rings, so the amount of waste to be disposed of safely in a sanitary landfill increases with the eco-innovations at hand, also affecting the above mentioned indicators;
- the scaling up of the eco-innovations from the lab scale to a pilot project plant one suggest possible improvements in all of the criticalities that have been illustrated so far, thus being likely to be worth further developments and consequent environmental assessments in future projects.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

6. LCA of GAIN's eco-innovations for oxygen supply

Based on previous GAIN's deliverable **D1.1** (Service *et al.*, 2019), on recent publication by Royer *et al.* (2021), and on parallel focus meetings, the following scenarios for the supply of liquid oxygen in trout farming were collaboratively designed and progressively double-checked by GAIN partners UNIVE and Troticoltura Leonardi as a conceptual basis for the environmental evaluation at hand:

- **scenario A ("Reference"):** constant seasonal supply of liquid oxygen, without short-term adjustments;
- **scenario B ("Green")**: focused on the environmental conditions of the Sarca river, which supplies water for the trout cultivation tanks, referred to as raceways, and then receives the effluent water from the same raceways; specifically, this scenario envisages that the water returned to the river should maintain the dissolved oxygen (DO) concentration of the water taken from it;
- **scenario C ("Welfare")**: focused on the desirable Dissolved Oxygen (DO) concentration for fish farming in the raceways, by specifically guaranteeing that the DO concentration never falls below a certain level, in order to guarantee fish welfare.

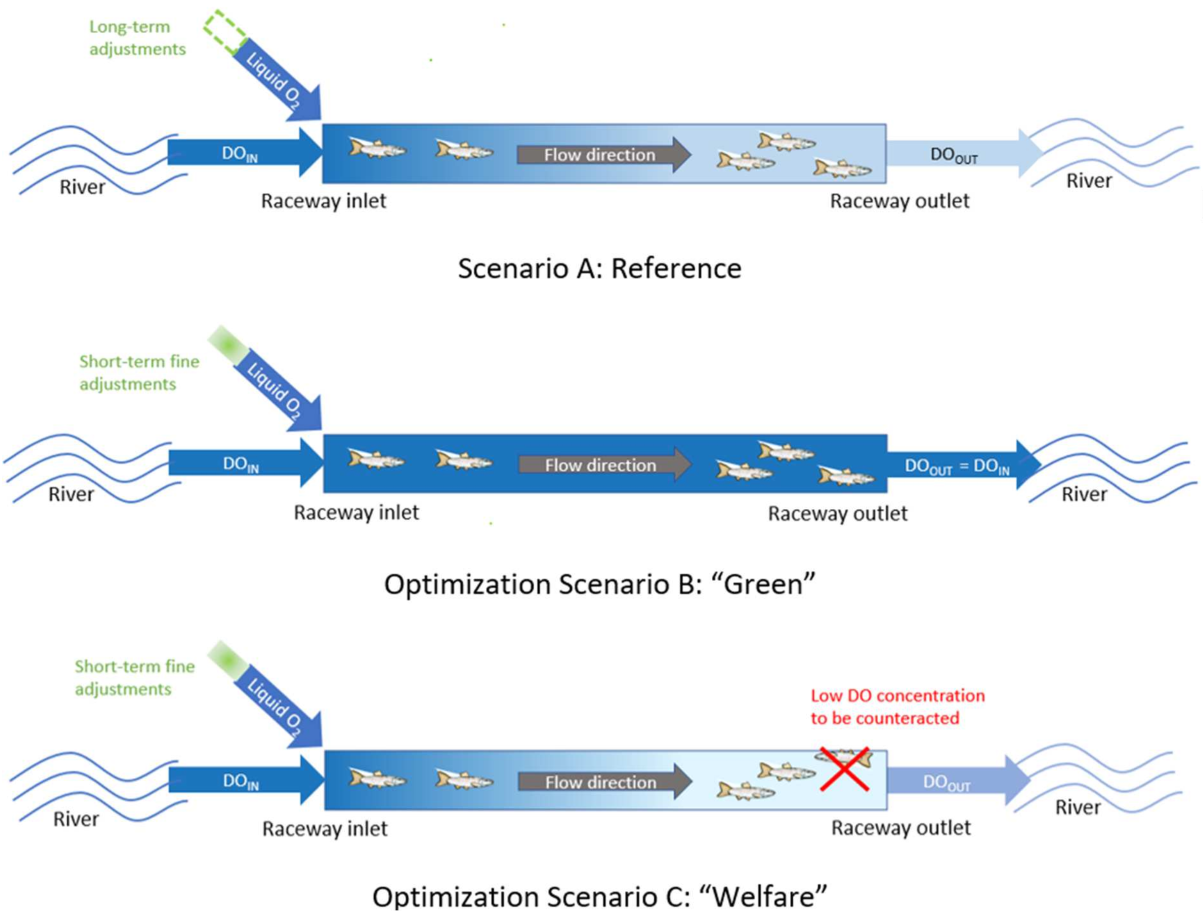


Figure 6.1 – Conceptual qualitative models for the oxygen supply (DO_{IN} = DO concentration at the raceway inlet; DO_{OUT} = DO concentration at the raceway outlet).

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Under scenarios B and C, the supply of liquid oxygen would be adjusted in real-time in response to the short-term variations in the oxygen demand. Scenarios A, B, and C are illustrated qualitatively in **Figure 6.1**.

A conceptual model of the system for the business-as-usual scenario at the selected plant in Preore (Trento), Italy was consequently built in LCA software environment SimaPro.

A reference **functional unit** (FU) of 1 ton of farmed rainbow trout was chosen for the studied plant, in order to ease possible comparisons.

For each of these scenarios, data were collected, organised, and allocated according to the chosen FU and – where applicable – to the lifetime of the inputs (e.g. machinery). The Life-Cycle Assessment at hand is mostly focused on the gains deriving from innovations, inspired by Precision Fish Farming (PFF), as detailed in the next sections. The qualitative flow chart for all of the four scenarios is presented in **Figure 6.2**, while numbers for each scenario are reported in **Table 6.1**.

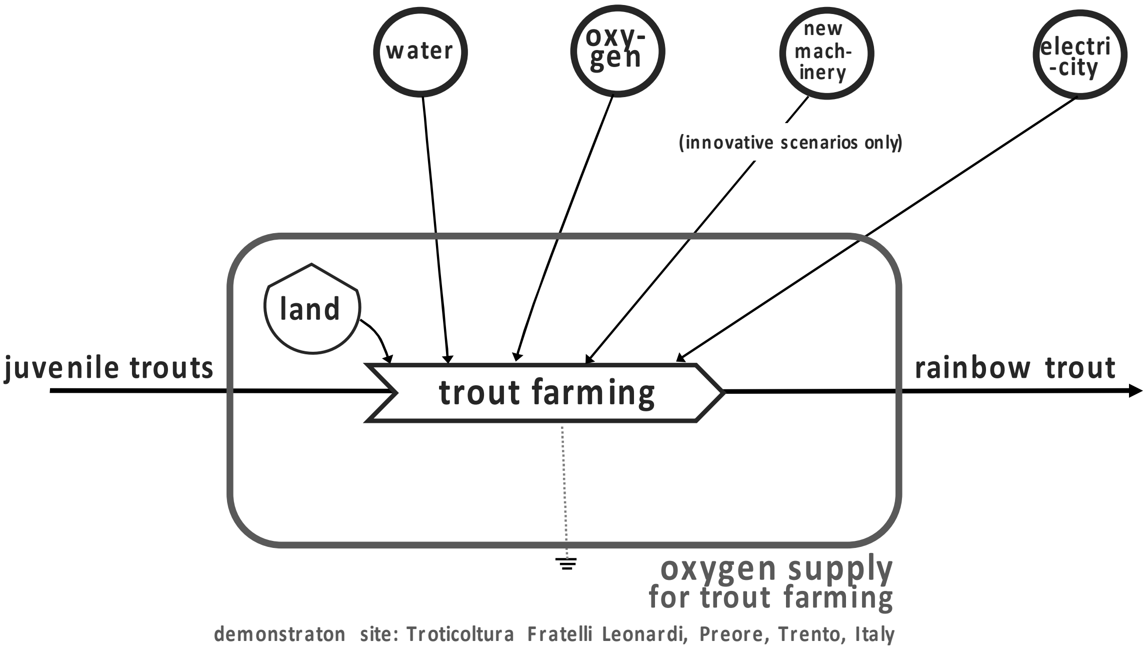


Figure 6.2 – Conceptual diagram for oxygen supply for trout farming

Table 6.1. Quantitative features of oxygen supply scenarios

Input	Unit	Scenario A ("Reference)	Scenario B ("Green")	Scenario C ("Welfare")
Land	m^2*a	1	1	1
Water	m^3	4.4 E+05	4.4 E+05	4.4 E+05
Oxygen	m^3	349	304	27
New machinery: sensor	kg	0	3 E-05	3 E-05
New machinery: automatic valves	kg	0	3 E-03	3 E-03
Electricity	kWh	30.6	31.3	31.3

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

6.1 Main eco-innovations for oxygen supply optimisation within GAIN

Because of the higher availability of freshwater that suits trout welfare (low temperature and high oxygen concentration), Northern Italy concentrates most of the trout farms in Italy (80%) and is also the major producer in volume (75%) (Castiglione *et al.*, 2009). In this region, trout farming is a traditional activity and the farming landscape is made of many small family-run activities, where the introduction of technological innovation can be restrained by a low investment capacity. After feeding and labour, dissolved oxygen (DO) is one of the main (monetary) cost items in trout farming (Castiglione *et al.*, 2009): therefore, optimising oxygen supply is of key importance in improving profits. Furthermore, improving oxygen supply control is of major importance for fish welfare and productivity, as low concentrations cause stress and decrease fish appetite, and environmental impact (as water used within the farms is then returned to the streams).

The control and optimisation of oxygen supply require a fully dynamic approach, as the DO concentration may rapidly change in relation to the concentration in the influent as well as to a set of processes occurring within a farm, such as fish oxygen consumption rate, photosynthesis, and bacterial activity, which are all affected by water temperature (Royer *et al.*, 2021). The Troticoltura Leonardi trout farm (Site 8 among the pilote sites of GAIN's WP1 activities, as further described below in section 6.1.3) is representative of the technology level of trout farming in Italy and thus represents an adequate case study to design innovation strategies that can support farmers in their day-to-day decisions.

Within Troticoltura Leonardi, liquid oxygen is currently stored in a steel tank connected to a network of pipes that independently distribute the oxygen to the raceways. The oxygen flow to each raceway is regulated through manual valves and the corresponding rates of oxygen supply are set by the farmer using their experience-based knowledge. Their strategy consists in trying to avoid a lack of oxygen for fish, taking into account the maximum respiration rate they can foresee given the biomass within the raceway and the environmental conditions. The work conducted under GAIN's WP1 allowed to collect data regarding the water quality and the biomass within the raceway, and to implement a dynamic model coupled with a data assimilation method. A subsequent assessment (Royer *et al.*, 2021) indicated that there is generally an overconsumption of liquid oxygen. In fact, under the current system, where the control of the oxygen supply relies on the operator, short-term adjustments to the oxygen supply to face the varying demand are not feasible. Such a system is here defined in scenario A. The optimisation scenarios envisaged, detailed afterwards, are instead referred to as scenarios B ("Green") and C ("Welfare"). The oxygen consumption for each scenario is estimated based on the same standard operational year. In each year, it is assumed that a new rearing cycle in the raceways begins in early April. Each cycle lasts 24 months, such that two cycles take place simultaneously at the farm, shifted by the period of one year. Therefore, the production and consumption of a full 24-month cycle are equal to the production and consumption of the standard operational year (12 months), assuming that the cycles are equal. Based on real data of feeding, temperature and mortality, the fish growth is estimated using a bioenergetic model specific for trout (Bolzonella *et al.*, 2021). In the following lines, a quantitative summary for the reference unit of the simulated model, to be later adjusted based on the chosen functional unit (FU), as done per **Table 6.1**, is presented[9].

[9] Common data for the three scenarios A, B, and C.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

- Initial fish weight at the rearing cycle: 2.7 g
- Initial fish population: 400,000
- Fish weights at harvesting: 500 g, 800 g, and 2.3 kg
- Total fish biomass production: 143 ton (50% at 500 g, 30% at 800 g and 20% at 2.3 kg)
- Number of operational raceways: up to 6, variable upon the fish biomass
- Maximum fish biomass per raceway: 25 ton
- Land use: 1 ha
- Water volume in each operational raceway: 1,280 m^3.
- Water flow rate in each operational raceway: 1,584 m^3/h
- Total water consumption: 6.3 x 10^7 m^3/year

Scenario A exhibits the following key inputs and requirements:

- supplied oxygen rate per operational raceway: 2.4 m^3/h, for 6 months (April to September)
- total supplied oxygen volume: 49,944 m^3/year
- supplied oxygen approach: manual
- machinery for oxygen supply: valves, network of pipes, tank, pump
- machinery power: 1 kW (estimated based on general technical survey)
- machinery operation: 6 months / year
- electricity consumption: 4,380 kWh

Dissolved oxygen is purchased as liquid oxygen for industrial use, usually produced in Italy, and supplied into the water basins through a distribution network of pipes and manual valves, which are still present in all scenarios and are therefore neglected for the purposes of the present assessment. Also basin structures, valves, and other plant pipes and machinery are neglected inasmuch as (i) they are common to the three scenarios, (ii) the entire assessment of trout production is beyond the purposes of the present study and of the project in general, (iii) there was a lack of information about them, and (iv) their expected contribution should be anyway divided by their lifetimes, thus significantly reducing their amounts to orders of magnitude that are not comparable with annual consumable inputs.

The overconsumption of liquid DO was the main reason for investigating innovative scenarios of oxygen supply. In the light of the above, short-term adjustments were not designed as manually driven, but rather resorting to some technological devices. The Precision Fish Farming (PFF) approach (Føre *et al.*, 2018) aims at supporting optimal management decision-taking by feeding predictive models with real time-data for environmental variables. Following this paradigm, the nowaday availability of sensors, along with the current development of data driven models and algorithms, has opened up the opportunity for implementing a cost-effective automatic control of oxygen supply, based on the short-term prediction of oxygen demand (Royer *et al.*, 2021). In order to evaluate the benefits of such an innovation, two alternative scenarios are envisioned for the implementation of the oxygen control system, referred to as "Green" (scenario B) and "Welfare" (scenario C), as shortly introduced above. The oxygen control system used for both scenarios consists in the introduction of an automated oxygen valve for each raceway along with electrical connections that allows to control the valve setpoints from an already existing computer. Depending on the scenario, the environmental parameters (oxygen - inlet and outlet- and temperature) measured by the existing probes, and the biomass within the raceway, the control software will adjust the automated valve setpoint.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Scenario B ("Green"):
This scenario aims at combining dynamic model and real-time data acquisition using data assimilation method (Kalman filter), in order to build reliable forecasts of fish respiration rate and DO concentration within the raceway. Based on this forecast it is possible to compute the oxygen supply that allows to give back to the stream water whose DO concentration is identical to water at the inlet. This means supplying a quantity of oxygen equal to fish demand. Scenario B ("Green") ensures that water returned to the stream (after fish respiration "subtraction") will always present the same level of oxygen as the one at the inlet, and will then not affect the DO concentration of the stream. Based on data collection, this scenario could be the first step of innovation as it is expected to allow to save some quantity of oxygen, minimising the risk regarding the water quality in the outlet. Compared with reference Scenario A, the changes consist here in substituting the manual valves with automated valves, and to implement a software module connected to them and to the sensors. This module will periodically compute both the oxygen supply and, then, the setpoint of such valves. Scenario B's main expected benefits consists in oxygen saving and water quality preservation.

Scenario C ("Welfare"):
This scenario aims at combining dynamic model and real-time data acquisition using data assimilation method (Kalman filter), in order to build reliable forecasts of fish respiration rate and DO concentration within the raceway. Based on this forecast it is possible to compute the oxygen supply that allows DO concentration within the raceway not to fall below a welfare threshold. The value of 8 mg/L was chosen based on the farmer's experience (and compatibly, among others, with Boyd *et al.*, 2018) and the emergency procedure presently operating within the farm. Scenario C ("Welfare") ensures that DO concentration will always remain above a welfare threshold for trouts: it should be more efficient from the oxygen supply point of view. Based on the data collection, this scenario could be the second step of innovation, as it is expected to allow for the saving of a higher quantity of oxygen than scenario B, minimising the risk regarding fish welfare. Compared with reference Scenario A, the changes consist here in substituting the manual valves with automated valves, and to implement a software module connected to them and to the sensors. This module will periodically compute oxygen supply and then the setpoint of such valves. Scenario C's main expected benefits consists in oxygen saving.

Granted that (i) all data refer to the modelled quantities (143 ton) and have to be adjusted to the chosen FU (as per **Table 6.1**), and (ii) common data to all scenarios have been provided above, in the simplified LCA that is here offered, Scenarios B and C exhibit the following key inputs and requirements:

Scenario B ("green")

- total supplied oxygen volume: 43,538 m^3/year
- supplied oxygen approach: automated (software control)
- additional machinery: automated valves + one sensor
- additional machinery power: + 0.024 kW (estimated based on general technical survey)
- machinery operation: 6 months/year
- electricity consumption: 4,380 kWh + 104 kWh = 4,484 kWh

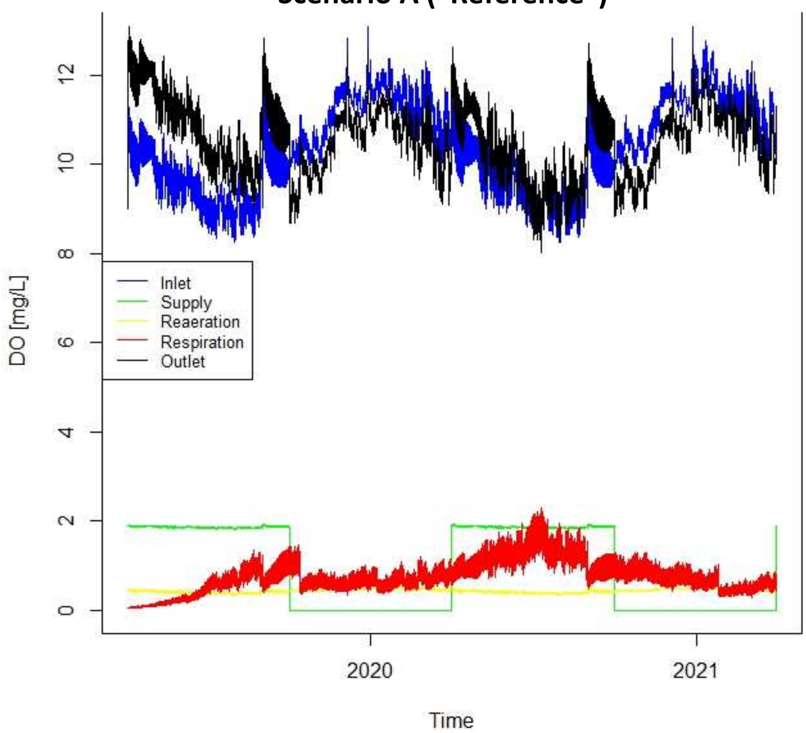
The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Scenario C ("welfare")

- total supplied oxygen volume: 3,897 m^3/year
- supplied oxygen approach: automated (software control)
- additional machinery: automated valves + one sensor
- additional machinery power: + 0.024 kW (estimated based on general technical survey)
- machinery operation: 6 months/year
- electricity consumption: 4,380 kWh + 104 kWh = 4,484 kWh

Figure 6.3 shows the concentration of dissolved oxygen broken down by subcomponents, for a single raceway which carries fishes from a complete rearing cycle (i.e., 24 months) up to the limit of 25ton of biomass, and which assumes harvesting at 500 g, 800 g and 2.3 kg (50%, 30%, and 20% of the total reared biomass, respectively). The DO subcomponents are specifically the DO at the raceway inlet and the outlet, the positive DO feedbacks owing to the supply of liquid oxygen and reaeration, and the DO consumed by fish respiration. For Scenario A, it can be verified from the figure that the DO concentration at the outlet is often higher than in the inlet, which clearly indicates overconsumption of DO. In addition, the concentration of DO never falls below the critical value of 8 mg/L. In line with the current practice, it can be verified that the supply of liquid oxygen from April to September responds to a higher consumption by fish respiration around these months. For Scenario B, the graphs depicted for the inlet and outlet are, as expected, nearly coincident. And so are the curves for the supply and respiration, indicating that the supply has to be adjusted to be nearly equal to the demand by the fishes, with the feedback of reaeration playing a minor role. For Scenario C, the oxygen supply is activated only around summer. And as in Scenario B, a daily oscillation pattern can be verified.

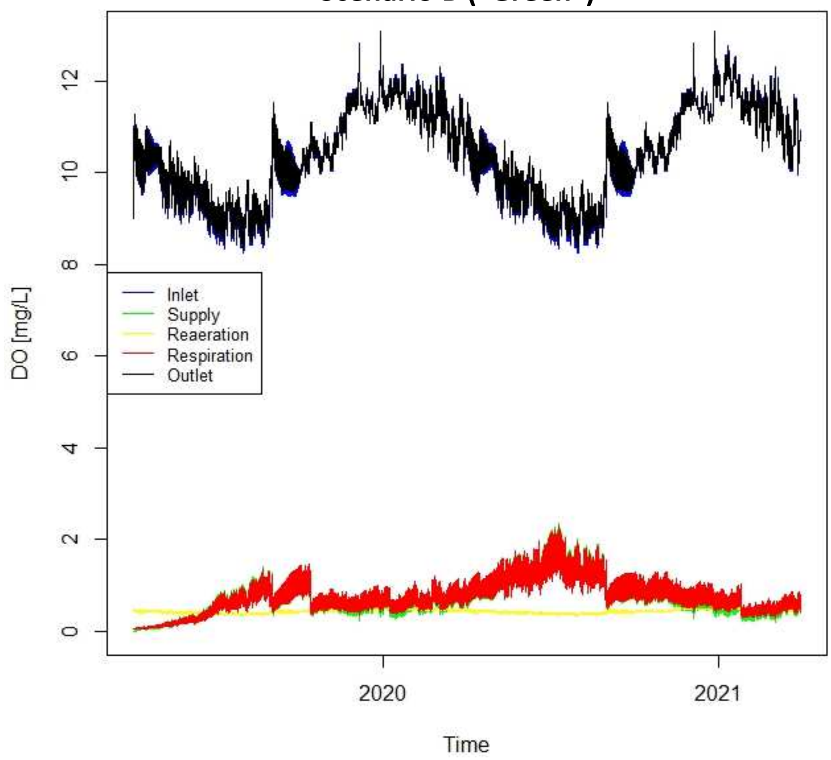
Scenario A ("Reference")



(a)

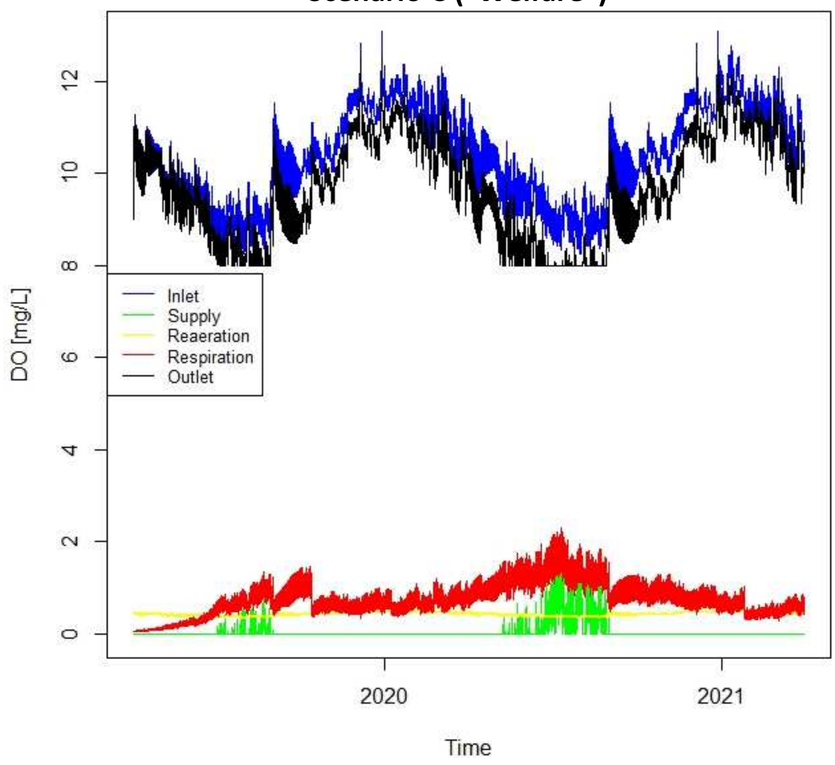
The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Scenario B ("Green")



(b)

Scenario C ("Welfare")



(c)

Figure 6.3 (a, b, c) – DO concentration in a single raceway along a 24-month rearing cycle

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

6.1.1 Main features of eco-innovations for oxygen supply compared to business-as-usual

Introducing an automated oxygen control for each raceways aims a fine tuning oxygen supply following short-term (within a day, due to circadian rhythm and digestion) and mid-term (due to evolution of environmental forcings) variations of oxygen demand by fish. The current distribution system of oxygen supply does not present any versatility with regard to these variations and could then be highly improved using a forecast approach of oxygen demand based on measurements and model output.

The technical modifications required by such innovation do not seem demanding from an economical point of view as the main components (valves and wires) do not represent an important investment and most of the "intelligence" will consist in a software component able to analyse available data (environmental parameters and fish parameters) in order to take a decision (oxygen valve setpoint) that is today already in the hands of the farmer.

The introduction of such a control will lead to a better control of the rearing conditions within the raceway and will then help the farmer in ensuring fish welfare, and fish growth. Scenario "Green" could also ensure a higher water quality in the effluent.

Forecast capacity of the dynamic model also allows to build an early warning system when oxygen levels in the effluent constantly decrease in spite of oxygen supply augmentation. This system could be useful when facing unexpected conditions or events (anoxia within the water stream, failure of oxygen supply system, …).

6.1.2 Quick presentation of the pilot demonstration site

The pilot site is located in the municipality of Preore, in Northern Italy, near the city of Trento. In this area, rainbow trout (*Oncorhynchus mykiss*) farming is a well-established, traditional activity. The site (**Figure 6.4**) is owned by Troticultura Fratelli Leonardi; a GAIN committed end user. The company produces its own fingerlings, which are subsequently transferred to six 200 m long, 8 m wide raceway basins. The raceways are covered by protection nets, in order to avoid bird predation, and are equipped with oxygen supply systems. The influent quality varies in time, as the water is withdrawn from the Sarca river. And, after flowing through the cultivation tanks, the water is discharged back to the Sarca river. Prior to its inflow into each raceway, water taken from the Sarca river receives a point source of oxygen, in order to face the oxygen demand by the fish respiration and to guarantee the water quality both in the raceway and afterwards when it is returned to the river. The farm is equipped with a tank which stores liquid oxygen and supplies each raceway independently via a distribution network. Oxygen is gasified in contact with ambient temperature and then dissolved in water at atmospheric pressure using a Low Head Oxygenator (LHO) system designed and manufactured by the farmer himself. Oxygen supply to each raceway is made through a manual valve controlled by the farmer and set to a nominal value. The LHO is characterised by an Oxygen Transfer Efficiency (OTE) of 90%. The farm is equipped with sensors for real time monitoring of water temperature and dissolved oxygen. These parameters are measured in the input water and in the middle of each basin. Data are processed and visualised using a dedicated proprietary software: at present, operators decide when to activate the oxygen supply on the basis of this information. The oxygen supply rate is controlled by manual valves.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Figure 6.4 – The demonstration plant for oxygen supply optimisation in Preore, Trento, Northern Italy (courtesy of Troticoltura Leonardi, http://www.troticolturaleonardi.com/)

6.2 Scenario-specific accounting choices and assumptions

A reference **functional unit** (FU) of 1 ton of harvested rainbow trout was chosen, adjusted to the reference value of 143 ton used for the modelling of the oxygen supply optimisation scenarios. Comprehensive results concerning the application of LCA to the whole rainbow trout are presented in Maiolo *et al.* (2020). For each of the above described three scenarios, data for Reference and Oxygen optimisation scenarios were collected, organised, and allocated according to such FU and – where applicable – to the lifetime of the inputs: basin structures, pipes, existing manual valves, and other plant machinery that are common to all scenarios were neglected for the purposes of the present assessment. In fact, their expected contribution should be negligible on annual basis, as their lifetimes range from 20 to 50 years or more. The water was computed as water, unspecified natural origin, in Italy. Directly occupied land was elaborated as grassland, natural, for livestock grazing. Electricity was elaborated as medium voltage from the Italian country mix. Fish feed was neglected inasmuch as common to all the scenarios, and potentially representing a bias as shown in **Chapter 4**. Dissolved oxygen was calculated as Dissolved oxygen, cryogenic, from Europe, considering a density of 6 mg/L = 0.006 kg/m^3. Computer and router for PFF were also neglected since common to all scenarios, and already running continuously for monitoring reasons. The additional sensor (assumed as having a mass of 0.05 kg and a minimum lifetime of 10 years) was computed as a mix of Diode, glass-, for surface mounting (global) and Integrated circuit, logic type (global). Electronic products were assumed to yield, at the end of their lifetime, a 5% mass of electronic scrap (valuable metals to be reused) and 10% of global average. The cables were ignored since a circuit is already present at the plant. The new valves – assumed as eight valves, with a mass of 1 kg each, 20-year lifetime, and a power of 4 W each – were computed as chromium steel, for electric use, referred to European steel product manufacturing; steel machinery is assumed to be recycled at the end of its life cycle, with a mass-to-mass recycling efficiency of 85% (based on Broadbent, 2016) yielding downgraded low-alloyed steel.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

6.3 Life-Cycle Impact Assessment (LCIA) results

The results of the LCA-based environmental evaluation of the selected scenarios for GAIN's eco-innovation at hand are illustrated in **Table 6.2**, showing the impact categories indicators of UNIVE's proposal for oxygen supply compared to business-as-usual. The proposal is divided into two sub-scenarios, as per the solutions described above: "Green" (B) and "Welfare" (C). The rationale behind the indicators and their description has been provided in **Chapter 2**, together with the used methods, as specified in the last column of **Table 6.2**. Percentage data come from the comparison between the otimisation scenarios (B and C) with the reference scenario (A).

Table 6.2. Life-Cycle Assessment indicators for GAIN's optimisation of oxygen supply

Impact category	Unit	Scenarios			Comparison with A		Method
		A	B	C	B	C	
Global Warming Potential, 100a	kg CO_2 eq	14.5	14.7	13.6	1%	-6%	[a]
Stratospheric ozone depletion	kg CFC11 eq	1.7E-05	1.8E-05	1.7E-05	2%	-3%	[b]
Terrestrial acidification	kg SO_2 eq	0.10	0.11	0.10	2%	-3%	[b]
Eutrophication, freshwater	kg P eq	5.2E-03	5.4E-03	4.4E-03	3%	-17%	[b]
Eutrophication, marine	kg N eq	3.8E-04	3.8E-04	3.0E-04	0%	-20%	[b]
Mineral resource scarcity	kg Cu eq	0.011	0.015	0.013	31%	20%	[b]
Fossil resource scarcity	kg oil eq	4.07	4.13	3.86	1%	-5%	[b]
Water consumption	m^3	4.4E+05	4.4E+05	4.4E+05	0%	0%	[b]
Cumulative Exergy Demand	MJ	2.2E+07	2.2E+07	2.2E+07	0%	0%	[c]
Land occupation	$m^2 * a$	1.40	1.41	1.30	1%	-7%	[d]
Biochemical Oxygen Demand	kg	5.8E-03	5.9E-03	5.6E-03	3%	-2%	[d]
Land use	Pt	233	234	225	0%	-3%	[e]

Method key: [a] IPCC GWP 100a; [b] ReCiPe 2016 Midpoint (E); [c] Cumulative Exergy Demand; [d] Selected LCI results V1.4; [e] Ecological Footprint Method (adapted) V1.00 / Global (2010)

6.4 Discussion

The selected LCA indicators show different trends in scenario B and scenario C. In particular, scenario C performs better than scenario B, due its larger oxygen savings: –92% versus –13%. In scenario B, no decrease was found in any indicator. In some events, some values stay the same: Marine eutrophication, Water consumption, Cumultive Exergy Demand, and Land use. Water consumption and Cumulative Exergy Demand stay the same also in scenario C; these indicators tend to exhibit the highest order of magnitude, connected to the non-changed or slightly changed inputs, and this might affect their indifference regarding the PFF proposals for the optimisation of the oxygen supply. In scenario C, all the remaining indicators show decreases ranging from timid –2% (Biochemical Oxygen Demand) and –3% (Stratospheric ozone depletion, Terrestrial acidification, and Land use) up to –17% (Freshwater eutrophication) and –20% (Marine eutrophication), likely linked to the saved liquid oxygen for industrial uses. In both scenario B and scenario C, the worst changes are anyway related to Mineral resource scarcity, the latter increasing by at least +20%. This can be associated with the fact that the oxygen savings following optimisation by PFF are obtained by the use of yet

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

small quantities of machinery – sensor and automated valves – requiring mineral inputs, whose depletion and processing impacts are evident in some indicators. In the optimisation scenario with lower oxygen savings, environmental costs overcome environmental benefits; not completely marked but still much better results are reached in scenario C, when higher oxygen savings are achieved.

6.5 Conclusion

Towards generalisation and/or exportation elsewhere, the following ought to be considered:

- The environmental implications of oxygen supply via PFF-inspired sensors and automated valves suggest overall improved environmental performances when oxygen savings are relevant (here, – 92%).
- No improvement was detected with smaller oxygen savings (here, –13%)-
- In both optimisation scenarios, the indicator Mineral resource scarcity undergo some marked worsening (+20%); in this case, the upstream resource requirements connected to the technological hardware do not offset the oxygen savings.
- For the farm analysed here, one of the proposed solutions requires significant less liquid oxygen than the other, and environmental consequences are more clear than in the scenario with reduced savings; however, for a different farm, this remarkable difference may not be the case, due to different water quality of the source and different dimensions and operational conditions of the cultivation tanks.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7. LCA of marine ingredients

7.1 State-of-the-art of life-cycle inventories on marine ingredients

Marine ingredients are produced from the rendering or other processing (e.g. hydrolysation) of raw materials derived from fish or other aquatic organisms into meals and oils for inclusion into feeds. Despite reductions in inclusion levels within aquaculture and other livestock feeds due to price and availability, marine ingredients are still considered an essential part of many aquaculture diets, particularly for carnivorous, high-trophic marine finfish, commonly cultured in the EU, UK and Norway (Kok *et al.*, 2020). However, the resolution and completeness of Life-Cycle Inventory (LCI) data for marine ingredients is poor, relying on a few database entries for a few key species. In contrast, the heterogeneity of marine ingredients use is very expansive, not only in the number of species used but also the variability within species, including fish, molluscs, crustaceans, macro and micro algae. There is a large variation in fishing effort required between different fishing techniques, such as bottom trawlers vs purse seiners but also within the same fishing techniques, depending on distance travelled by fishing boats and catch per unit effort (CPUE). By-products from fishery and aquaculture processing are also increasingly used for the production of marine ingredients, with a large unrealised potential (Jackson & Newton, 2016) and have varying footprints based on the fishing methods and also processing efficiency. Emissions may then be influenced by the electricity mix of countries in which the processing and rendering occurs.

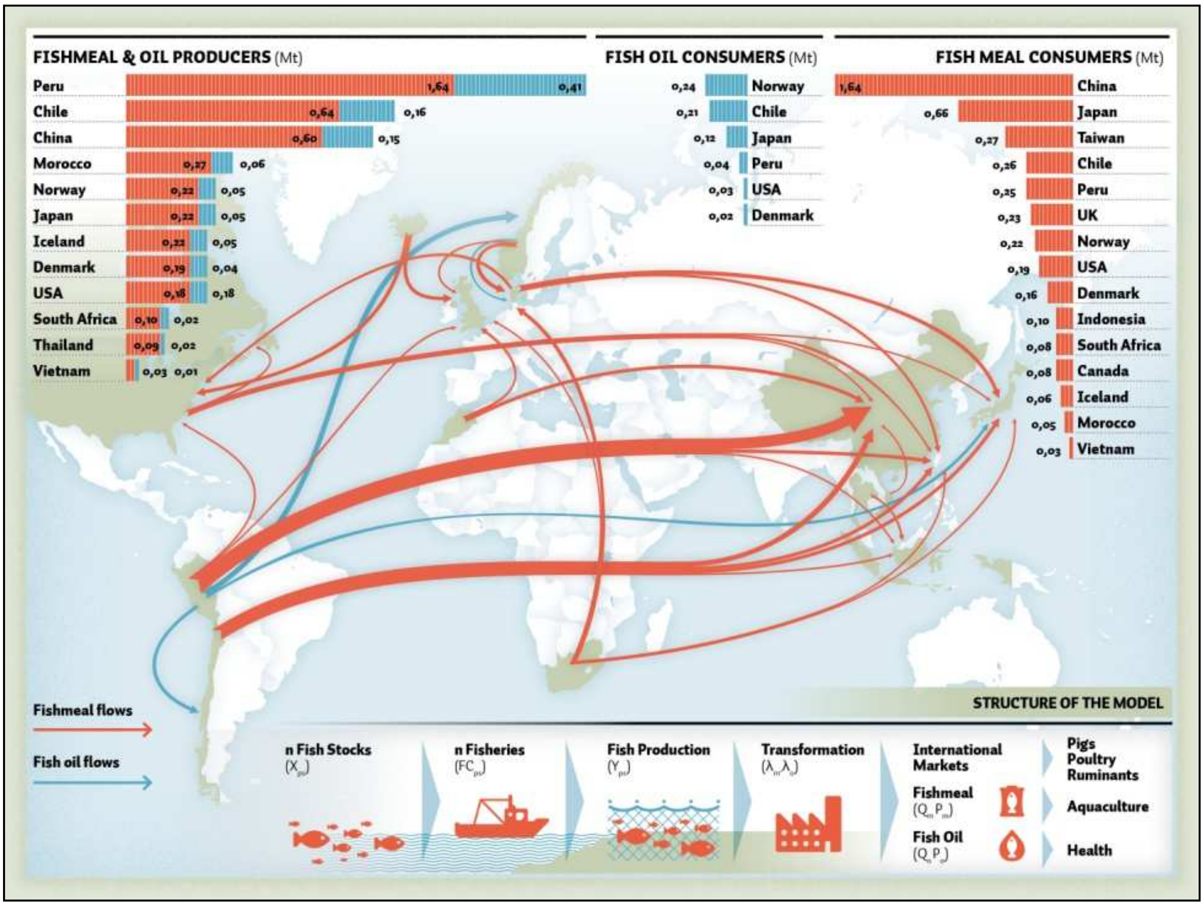


Figure 7.1 – Merino *et al.* (2010)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

The marine ingredients industry relies on global value chains that satisfy world aquaculture and other livestock production (**Figure 7.1**). The species used for rendering are dependent on location and their relative local markets for human consumption and other markets (Kok *et al*., 2020) but there are several key fish species, notably anchoveta (*Engraulis ringens*) which represents around a third of global fishmeal supplies (**Figure 7.2**). Other key species such as herrings, mackerels and sardines are used in varying amounts for marine ingredients or direct human consumption, sometimes with the by-products directed to marine ingredient production.

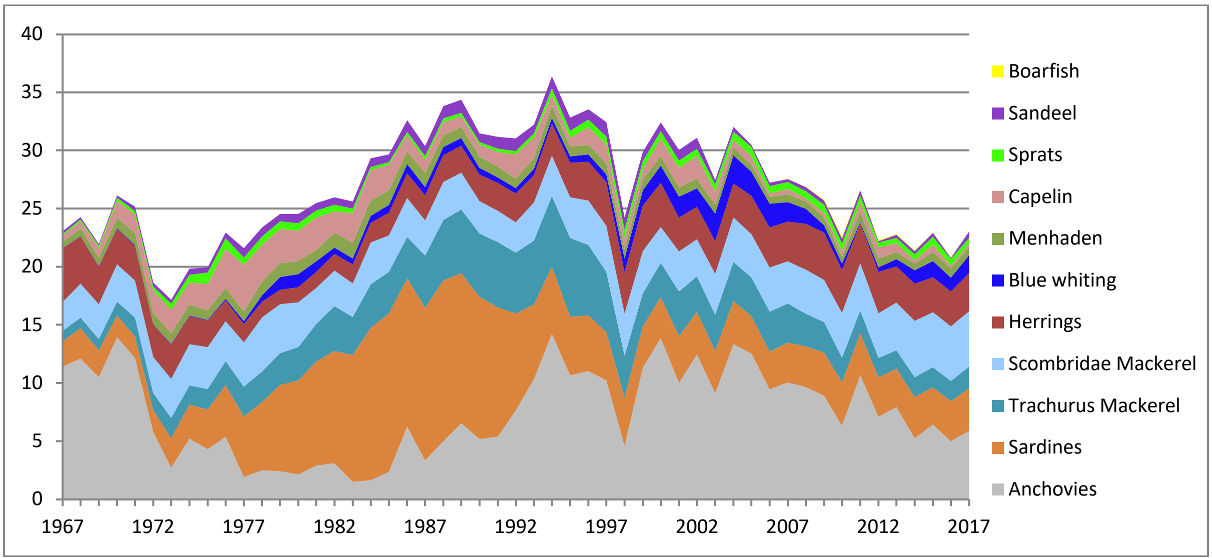


Figure 7.2 – Global catches (million tonnes) of most important fish species for reduction into marine ingredients (data from FAO, 2019)

Anchoveta has been well characterised in publications by Fréon *et al.* (2014) and Avadí *et al*. (2014), but other marine ingredients are poorly represented in LCA databases. A paper by Cashion *et al.* (2016) provided a compilation of basic reference data from various sources for marine ingredients produced from some of the key species above, but there were some issues regarding the resolution and reliability of the data. For example, most of the ingredients documented were from Norway, despite much higher variability in the commercial ingredients list. In addition, all data in Cashion *et al.* (2016) was calculated using a mass allocation basis, while the EU's final Product Environmental Footprint Category Rules (PEFCRs) for feed ingredients require an economic allocation for utilisation of by-product resources. For those reasons we sought to provide a more detailed analysis of marine ingredients provision using economic allocation for mixed fisheries, processing of fish to different co-products and rendering into fishmeal and oil. The data in this report provides basic LCA results for marine ingredients along with eFIFO[10] (Kok *et al.*, 2020) and Biotic Resource Use (based on Pauly and Christensen, 1995), which are considered key indicators for marine ingredients use. Further indicators are being included within the EISI (GAIN's deliverable **D4.3**) according to data availability within the literature.

[10] Economic FIFO (First in First out)

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7.2 Marine ingredients included in GAIN

The marine ingredients assessed in GAIN were those indicated to the project by major feed producers included within the Eco Intensification Sustainability Index (EISI) work which provides a benchmark for some of the key European aquaculture species. The ingredient list is provided in **Table 7.1** together with the availability of data. Where specific data could not be found, a representative figure was estimated using a NUSAP[11] pedigree to horizontally average similar data from other enterprises (Henriksson *et al.*, 2013) as described below. For example, specific data could not be found on the energy requirements for rendering of most fish species to fishmeal and oil and a default average was estimated from anchovy and sandeel rendering data. Processing data was only relevant for calculating the emissions related to the production of by-product raw material sources, including mixed white fish, herring and mackerel.

Table 7.1. List of marine ingredients modelled within the GAIN project (P) indicates primary data, otherwise data was obtained from literature resources

Species	Origin	Fishery data	Processing data	Rendering data	Yield data
Anchoveta (*Engraulis ringens*)	Peru	✓	-	✓	✓
Blue whiting (*Micromesistius poutassou*)	IS, NO	✓	-	x	✓
Capelin (*Mallotus villosus*)	IS, NO	✓	-	x	✓
Atlantic herring (*Clupea harengus*)	DK, IS, NO	✓	✓	x	✓
Norway Pout (*Trisopterus esmarkii*)	NO	✓	-	x	✓
Sandeel (*Ammodytes marinus*)	DK	✓	-	✓	✓
Indian Oil Sardine (*Sardinella longiceps*)	Oman	✓	-	x	✓
California pilchard (*Sardinops sagax*)	Panama, Mexico	✓	-	x	✓
Gulf Menhaden (*Brevoortia patronus*)	USA	✓	-	x	✓
Atlantic mackerel (*Scomber scombrus*)	DK, NO	✓	✓	x	✓
Atlantic horse mackerel (*Trachurus trachurus*)	Spain	✓	-	x	✓
European sprat (*Sprattus sprattus*)	DK, NO	✓	-	x	✓
Sardine (*Sardina pilchardus*)	Spain	✓	-	x	✓
Krill (*Euphausia superba*)	Uruguay	✓	-	✓	✓
Mixed white fish by-product	UK	✓	P	x	✓

[Key: IS = Iceland, DK = Denmark, NO = Norway; UK = United Kingdom; USA = United States of America]

[11] Numeral, Unit, Spread, Pedigree and Assessment

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7.3 Methods

Calculations were made in Simapro 9 software using standard CML baseline approach. The following impact categories were included: Global Warming Potential, Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, Photochemical Oxidation Potential, with added impact categories of Consumptive Water Use, Biotic Resource Use (Cashion *et al.*, 2016) and economic Fish In Fish Out ratio (Kok *et al.*, 2020). The **functional unit** in all cases is 1 ton of production.

7.3.1 Data resources

The list of marine ingredients for this chapter was obtained from commercial feed producers who provided the species and origin of fishmeals and fish oils used within their formulations. The majority of data were obtained from an extensive literature search on LCAs of key fisheries for the species lists provided by major feed producers. Data on processing were obtained from one major white fish processor in the UK and from the recent SINTEF (2020) report on carbon footprints of Norwegian seafood products. Other processing data were found from several sources but rejected due to unreliability, as many of the inputs were several magnitudes different from the UK primary and SINTEF data which were broadly in agreement. Data on rendering the raw materials into fishmeal and oil was also difficult to obtain although a few papers did contain that information. One industry contact was not willing to provide primary data after several meetings and email exchanges.

The data sources for the fisheries are provided in **Table 7.2**, including the origin, literature source and specific details about the fisheries. Some data resources provided a full life cycle inventory with further allocation between species, but others only provided fuel intensity (litres or kilogrammes of diesel per unit catch) allocated to different species. Data for boat construction and maintenance were averaged for purse seiner and trawler fleets to create default processes that could be applied to fisheries where those data were missing. The default values were applied proportionately to fuel intensity to provide an estimate of the emissions related to boat construction and maintenance required per functional unit. Fuel intensity is considered to be the most important contribution to Global Warming Potential and is often given in either litres or kg of diesel per unit catch. However, fuel use in LCA software is usually determined in MJ of fuel combusted in (boat) engines. In this report a conversion of 0.0234 kg of fuel for every MJ was used with a density of 0.84 kg per litre of fuel. Data on processing came from UK primary data on white fish processing (demersal) as the most complete and up-to-date source. Data from SINTEF (2020) and Svanes (2011) only provided electricity consumption. However, SINTEF 2020 included electricity for pelagic fish processing which was combined and adjusted with the primary UK data using the NUSAP principles outlined below to produce estimated processes for Norwegian and Icelandic pelagic processing.

Rendering LCI data came from three data sources, two of which were for anchoveta and the other for sandeel. No other data was found for other species. Default rendering processes were created by horizontally averaging the data for the three other species and using appropriate energy mixes for where the rendering occurred.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table 7.2. Data coverage for fishing literature resources used in this chapter

Source	Species/ raw material used in marine ingredients	Fishing method	Origin	Data coverage	Allocation
Fréon et al 2014	Anchoveta	PS	Peru	FI, OI, BCM, R	NA
Almeida et al 2014	Sardine	PS	Portugal	FI, OI	M
Ramos et al 2011	Atlantic mackerel Sardine	PS	Spain	FI, OI, BCM	SE
Vasquez-Rowe et al 2011	Atlantic mackerel Atlantic horse mackerel Blue whiting Sardine	PS, BT	Spain	FI, OI, BCM	M, E
Vasquez Rowe et al 2013	Atlantic mackerel Atlantic horse mackerel Blue whiting	PS	Spain	FI, OI, BCM	M
Thrane 2004	Atlantic herring Atlantic mackerel Sandeel Mixed white fish	PS, BT	Denmark	FI, OI	M, E, SE
SINTEF 2020	Atlantic herring Atlantic mackerel Mixed white fish	PS, BT	Norway	FI, Pr	M
Svanes et al 2011	Mixed white fish	LL	Norway	FI, OI, BCM, Pr	M, E
Fulton 2010	Mixed white fish	LL	Iceland	FI, OI, BCM	M
Das and Edwin 2016*	Indian Oil Sardine	RS	India	FI, OI, BCM	M
Fisheries Iceland 2017	Blue whiting Capelin Herring Mackerel	MW PS PS MW	Iceland	FI	NM
Schau et al 2009	Blue whiting Capelin European sprat	MW PS PS	Norway	FI	M, E
Tyedmers 2004	European sprat	PS	Denmark	FI	M
Cashion et al 2016	Gulf menhaden California pilchard	PS	USA Mexico	FI, R	M
Parker and Tyedmers 2012	Antarctic krill	PS	Uruguay	FI, OI, BCM, R	En, SE

[PS = purse seine, BT = bottom trawl, MW = Mid-water trawl, LL = long line, RS= ring seine, FI = fuel intensity, OI = operational inputs, BCM = boat construction and maintenance, Pr = processing, R = rendering, M = mass allocation, E = economic allocation, En = Energetic content allocation, SE = system expansion, NA = not applicable (single species fishery), NM = not mentioned]

*The Indian oil sardine data from the feed companies was reported as from Oman, which uses beach seine harvesting techniques, i.e. there is no fuel or boat use. Only the data on net maintenance was used which was assumed to be similar to the ring seine method used in India.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7.3.2 Horizontal averaging of literature data

Where no primary data can be collected and literature values are used to create LCA processes, the data must be weighted and averaged according to uncertainty principles according to Henriksson *et al.* (2013). This approach incorporates three levels of uncertainty to determine the weighted average (i) the inherent uncertainty within the literature source, (ii) the representativeness of the literature data according to the Numeral, Unit, Spread, Assessment and Pedigree (NUSAP), and (iii) the "spread" of the variance between the different literature sources. The NUSAP approach assesses each data entry for its temporal, geographic relevance, its completeness, the sample size and its closeness to the industry in question i.e. whether it is from the exact or related industries or from a pilot plant etc. The scores from NUSAP and the inherent uncertainty contribute to the weighting of each data entry towards the overall "horizontal" average for each value.

7.3.3 Allocation

Many of the mixed fisheries data sets used mass allocation to determine the individual emissions data for each species. The EU's PEFCR require that feed ingredients are assessed using economic allocation. That is, the proportion of emissions and impacts attributed to co-products is determined proportionately to their value (i.e. the price x volume divided by the sum of the prices x volumes for all co-products). Although economic allocation provides challenges in seafood production, particularly for volatile mixed fisheries and for the comparative prices of by-product resources from processing, it is possible using long-term averages. Despite the challenges, applying an economic allocation to fisheries is fully justified when looking at the catch data for fuel intensive fisheries, e.g. for the Danish Norway lobster fishery that uses by far the highest amount of fuel of any fishery, Norway lobster only represents 19.4% of the catch by volume, but 57.7% by value. Economic allocation was determined for mixed fisheries using long term averages of commodity prices, calculated using FAO Fishstat data resource (FAO, 2019) and applied consistently to all literature sources reporting data for mixed fisheries. Full economic allocation data was usually not supplied (**Table 7.2**), however where they were, these data were not used for consistency between species, and often because the data were over a short time period e.g. Vasquez-Rowe *et al.* (2013). In the case of Schau *et al.* (2009), only the economically allocated values, in isolation were supplied and there was no way of cross-checking or recalculating the allocation factor using long-term FAO data. Antifouling emissions were given by several authors usually as ml/kg of fish landed, but there was little data on the composition of those emissions. The composition of the emissions was calculated from Fréon *et al.* (2014) and applied proportionately to each fishery. There was very little data found regarding the values of co-products from processing. SINTEF (2020) said that the main products were 28 NOK/kg and by-products were 3 NOK/kg. Svanes *et al.* (2011) also provided som economic allocation data but the processing fractions did not match those from the primary processing data and therefore economic allocation was difficult to determine for all by-products. Therefore, the SINTEF (2020) data was preferred but gave a higher allocation of impacts to by-products than Svanes *et al*. (2011) which determined that by-products were worth less than 1% per kg compared to the filleted cod loins. The utilisation of fishery by-products has much improved in the last ten years (Stevens *et al.*, 2018) and it is likely that the SINTEF (2020) value is more accurate.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7.3.4 Life-cycle inventories

7.3.4.1 Fisheries

A list of data inputs and outputs for different fisheries relevant to the supply of marine ingredients to the European Union, Norwegian, and United Kingdom aquaculture industries is presented in the **Annex**. Specifically, data are provided for: default boat construction and maintenance for purse seiner and trawler vessels (**Table A.1**); antifouling emissions composition (**Table A.2**); inputs and outputs per tonne of anchoveta fishery landed in Peru (**Table A.3**); inputs and outputs per tonne of Atlantic horse mackerel from both purse seiners (**Table A.4**) and bottom trawlers (**Table A.5**) in Spain; inputs and outputs per tonne of North-East Atlantic mackerel and sardine from fishery in Spain (**Table A.6**); inputs and outputs for Indian oil sardine from beach seine fishery in Oman (**Table A.7**); inputs and outputs per tonne of Antarctic krill fish from fishery in Uruguay (**Table A.8**); inputs and ouputs per tonne of fish from longline mixed fishery in Iceland (**Table A.9**); inputs and outputs per tonne of fish from autoline mixed fishery in Norway (**Table A.10**); inputs and outputs for Norwegian mixed fisheries (**Table A.11**), including coastal trawler fishery, coastal seiner fishery, pelagic trawler fishery, cod trawler fishery, purse seiner fishery, and ocean fishery; contribution of different Norwegian isheries to total catch per species (**Table A.12**); inputs and outputs for Danish mixed fisheries (**Table A.13**), including cod fishery, flatfish fishery, pelagic fishery, and lobster fishery; contribution of different Danish fisheries to total catch per species (**Table A.14**), and other fishery data as available for European and North American contexts (**Table A.15**).

7.3.4.2 Trophic levels of species

The trophic level of a species is linked to the **Biotic Resource Use (BRU)** indicator. BRU is a measure of the cumulative appropriation of biomass, measured in kg of C, given by the formula below:

$$BRU = \frac{\mathrm{C}}{\mathrm{M}} * \left(\frac{1}{TE}\right)^{TL-1}$$

Where C is mass of the catch, M is the ratio of biomass to Carbon content, TE is the transfer efficiency and TL is the trophic level of the species. According to Pauly & Christensen (1995) M is typically given as 9 and the TE is 10. BRU is not widely reported in LCAs but is considered important when reporting on the use of fisheries resources. Removal of higher trophic species is regarded as having a larger effect on marine ecosystems because they in-turn feed on lower trophic species and disproportionately affect the marine food web, whereas lower trophic species can regenerate more quickly. However, there is concern that by “fishing down the food web” (Pauly *et al*., 1998), the basis of the food web can be undermined, if fished irresponsibly. Therefore, BRU does not provide a comprehensive measure of how sustainable fishing activities are in regard to stock status and fisheries management and must be contextualised. In conjunction with Fish In: Fish Out ratios (FIFOs) and Forage Fish Dependency Ratios (FFDRs) a better understanding may be achieved. Certification bodies such as ASC (2017), GAA (2016), GlobalGAP (2019) also require that marine ingredients are sourced from sustainable fisheries. The trophic levels of the main marine ingredients species within GAIN, together with the BRU for 1 tonne of live fish, are all offered in **Table 7.3**.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table 7.3. Trophic level of main marine ingredients species and the BRU for 1 tonne of live fish

Species	Trophic level	SD	BRU, kg C / ton
Anchoveta (*Engraulis ringens*)	2.9	0.4	8826
Blue whiting (*Micromesistius poutassou*)	4.1	0.3	139881
Capelin (*Mallotus villosus*)	3.2	0.1	17610
Atlantic herring (*Clupea harengus*)	3.4	0.1	27910
Norway Pout (*Trisopterus esmarkii*)	3.2	0.0	17610
Sandeel (*Ammodytes marinus*)	3.1	0.1	13988
Indian Oil Sardine (*Sardinella longiceps*)	2.4	0.2	2791
California pilchard (*Sardinops sagax*)	2.8	0.1	7011
Gulf Menhaden (*Brevoortia patronus*)	2.2	0.1	1761
Atlantic mackerel (*Scomber scombrus*)	3.6	0.2	44234
Atlantic horse mackerel (*Trachurus trachurus*)	3.7	0.0	55687
European sprat (*Sprattus sprattus*)	3.0	0.1	11111
Sardine (*Sardina pilchardus*)	3.1	0.1	13988
Krill (*Euphausia superba*)	2.2	0.2	1761
Cod (*Gadus morhua*)	4.1	0.1	139881
Haddock (*Melanogrammus aeglefinus*)	4.0	0.1	111111

[BRU calculated according to Christensen and Pauly (1995) according to trophic levels from Fishbase.org]

7.3.4.3 Fish processing

Fish processing is only relevant for marine ingredients rendered form the fish by-products, including white fish species, Atlantic mackerel and herring. All other marine ingredients included within GAIN are from whole fish. A full primary data set was provided by one UK based white fish processor but the LCI is not included in this report due to confidentiality reasons. Data for pelagic processing was adjusted from the UK primary data with electricity consumption obtained from SINTEF (2020). Processing fillet yields for herring and Atlantic mackerel were assumed to be 52% according to FAO (1989).

7.3.4.4 Rendering

Fishmeal and fish oil rendering data came from two papers on anchoveta and from the Danish LCA food database[12] A generic process was developed using horizontal averaging of the data according to Henriksson *et al.* (2013) and applied to marine ingredients for which specific data could not be found, along with specific yield data for fishmeal and fish oil. The data for anchoveta rendering referred to the production of standard meal and superprime from four plants between the two data sources (**Table A.16** in the **Annex**). There was considerable difference between the sources on reported energy consumption and data from Fréon *et al.* (2017) was more complete than that from Avadí *et al.* (2014). There is also some uncertainty regarding rendering yields of meals and oils from sandeel and other species (**Tables A.17–A.18**). There are limited data for all of the species under study with many of the yields coming form Cashion *et al*. (2017). While Cashion *et al.* (2017) provide a comprehensive list of species and yields, there is little information on how they were derived and in comparison to the raw materials. Some yields are lower than would be expected compared to raw material properties and other data were not in agreement. For example, the oil yield for blue whiting is reported as 1.9% according to Cashion *et al.* (2017), whereas Lurdes *et al.* (1998) reported the lipid content of blue whiting as 11.3%. Alternative literature sources were sought and the most appropriate figures used based on the completeness of data where yields could be better matched to raw material attributes. Allocation of emissions and resource attribution between

[12] http://www.lcafood.dk/

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

fishmeal and fish oil was calculated economically based on global average prices from the OECD databases[13] over a five year average from 2014 to 2018 inclusive. Percentage yields of fishmeal and fish oil marine ingredients from selected species are offered in **Table 7.4** based on the cited literature.

Table 7.4. Yields marine ingredients from key species per 1 tonne of landed fish

Meal and oils	Source	Meal yield,%	Oil yield,%
Whole fish			
Anchoveta (*Engraulis ringens*)	Fréon et al 2017	23.8	4.5
Blue whiting (*Micromesistius poutassou*)	Cashion et al 2017	19.7	1.9
Capelin (*Mallotus villosus*)	Cashion et al 2017	16.6	7.7
Atlantic herring (*Clupea harengus*)	Cashion et al 2016	22.1	11.5
Atlantic mackerel ((*Scomber scombrus*)	Cashion et al 2016	19.4	18.6
Norway Pout (*Trisopterus esmarkii*)	Cashion et al 2016	20.4	11.5
Sandeel (*Ammodytes marinus*)	Danish Food LCA	21.5	4.5
Indian Oil Sardine (*Sardinella longiceps*)	Pravinkumar et al 2015	25.7	15.4
	Cashion et al 2017		
California pilchard (*Sardinops sagax*)	Cashion et al 2017	23.0	18.0
Gulf Menhaden (*Brevoortia patronus*)	Tacon et al 2006	21.0	16.0
Atlantic horse mackerel (*Trachurus trachurus*)	Cashion et al 2017	23.0	6.0
European sprat (*Sprattus sprattus*)	Cashion et al 2017	18.8	7.9
Sardine (*Sardina pilchardus*)	Parker and Tyedmers 2012	23.0	18.0
Krill (*Euphausia superba*)		14.4	0.07
Byproducts	Cashion et al 2017		
Cod (*Gadus morhua*)	Cashion et al 2017	17.0	1.7
Haddock (*Melanogrammus aeglefinus*)	Hilmarsdottir et al 2020	17.0	1.7
Atlantic herring (*Clupea harengus*)	Hilmarsdottir et al 2020	22.5	17.0
Atlantic mackerel ((*Scomber scombrus*)		22.5	17.0

7.4 Life-Cycle Impact Assessment (LCIA) results

A detailed presentation of the LCIA results for the marine ingredients listed in **section 7.3.4** is available in the **Annex** for key fishmeal (**Table A.19**) and fish oil (**Table A.20**) resources used in European aquaculture. The results show that there is considerable difference in the impacts between different species and locations. The main reasons for this are the different yields of meal and oil from different species and the fishing effort required to catch and land fish. To a lesser extent, the energy for rendering also plays a part, but only for a few species where that information was identified. In most cases default energy use was used for rendering, calculated as an average for the species where that data was available, according to **Table 7.1** with electricity mixes adjusted according to the country of production.

[13] https://www.oecd-ilibrary.org/agriculture-and-food/data/oecd-agriculture-statistics_agr-data-en

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7.4.1 Contribution analysis

7.4.1.1 Fisheries

Life-Cycle Impact Assessment results show that more emissions are associated with purse seiners than bottom trawlers per unit fishing effort, particularly GWP which is over five times higher (**Figure A.1** in the **Annex**). This is probably because purse seiner boats tend to be smaller than bottom trawlers. However, indications from the LCI suggest that CPUE is lower for species using bottom trawls, requiring more fuel intensity. Large contributions come particularly from nylon manufacture for nets in GWP, CWU and AP, copper manufacture for AP, EP, ODP and PCO. Wood is the main contributor for land use. The impact from various fisheries from which marine ingredient raw materials is highly variable between different species and the location from which they are fished. The variability is linked to fishing effort required, with the other major contribution from construction and maintenance of fishing boats as shown in **Figure A.2**; regarding the contributions to GWP from fuel use, boat and gear maintenance, refrigerants and ice, in most cases pelagic fisheries perform better than demersal, although there is a lot of variation between countries. Icelandic fisheries, tend to have the lowest fuel use and Danish fisheries the highest. Indian oil sardine from Oman has an especially low footprint because it is reported to be caught using beach seiners, with no fuel use, the only contribution coming from net maintenance. Fuel is the major contributor in all other cases, representing around 75% to 85% of GWP. Refrigerants and ice manufacture contribute negligibly to GWP. Some of the species catch are made up from several different fisheries within the national fisheries, such as pelagic trawls or bottom trawls that land several species as described e.g. in **Tables A.13 and A.14** for Norwegian and Danish fisheries respectively. The different types of fishery have different fuel intensities and different species mixes within their catch, the impact for which have been allocated according to economic values, averaged over several years as described above, therefor there is often a difference between the contribution in volume from the different fishery types compared to the contribution in impact as shown in **Figure A.3**. For example, different types of trawlers; cod, bottom and ocean, as well as Norwegian lobster fisheries had disproportionately large contributions to the overall GWP. These differences should be taken into account when comparing between fisheries of different nations. GWP is the most important impact category for fisheries, along with AP because they are both linked to fuel consumption. Other impact categories, such as CWU, LU and EP are relatively unimportant compared to other parts of aquaculture value chains. However, BRU is fairly unique to aquaculture LCAs, although it could also be important to consider where there are areas of land use change or primary forest is sourced as a raw material. Some remarks can be offered about the BRU values for the major marine ingredients species studies in this report, calculated according to trophic levels given by Fishbase.org (**Figure A.4**): the highest BRU is seen for higher trophic species such as gadoids and C accumulates by an order of magnitude for every point on the trophic level scale according to the calculation by Christensen and Pauly (1995).

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

7.4.1.2 Rendering

The main emissions from rendering processes are shown in **Figure A.5** in the **Annex**. Data was only available for rendering from three literature sources, providing five data points. Theses were horizontally averaged according to the method described by Henriksson *et al*. (2013) to give the default process used in the majority of cases. The major difference between Norway and the rest of the world is due to the electricity mix between the different locations. The GWP and the consumptive water and land use respectively for selected fishmeals compared to some important plant protein ingredients are shown in **Figure A.6**. The marine ingredients generally perform well against the plant ingredients for GWP emissions, especially low trophic species such as anchoveta, menhaden and the by-product meals from herring and mackerel. Soybean protein concentrate from Brazil (data from Agri-footprint, 2015) stands out because of its high carbon emissions resulting from land use change (LUC). Wheat gluten has especially high energy inputs for the wet-milling process, whereas Chinese pea concentrate has high production emissions at the farm. Although a default process is used for the rendering of most fish meals, there are differences in the contribution, resulting from different yields of meals and oils per unit raw material, to which the energy use is related. White fish by-products and capelin had particularly low overall yields of oil and meal respectively, whereas higher yields came from sardine species. Marine ingredients, somewhat surprisingly, show slightly higher water consumption than plant ingredients which is mostly due to the use of nylon in the fishing stage which may be an over-estimate. Land use for marine ingredients is predominantly from providing wood for fishing boats and for some biomass energy provision in the supply chains of the rendering process, mostly related to copper. Land use for plant ingredient is directly from the farming stage which shows pea concentrate from China to have the highest dependency. Although this is from already converted arable land so there is little effect from LUC as seen from soybean protein concentrate. The GWP, CWU and LU of selected fish and plant oils relevant to aquafeed formulations are illustrated in **Figure A.7**. Again, marine ingredients perform well against plant ingredients, especially by-product meals and those from small pelagic species, such as anchoveta and gulf menhaden. Surprisingly, GWP effects due to LUC are higher for Dutch rapeseed oil than for palm oil from Malaysia. However, plant ingredient data were taken from the Agri-footprint (2015) database directly and cannot be easily verified. Typically, water consumption trends follow those of fishmeals with high quantities used in the manufacture of nylon used for net manufacture and maintenance. Land use is higher for plant ingredients as would be expected. The trade-off between land use and biotic resource use is key for provision of aquafeed ingredients. As more marine ingredients are replaced with terrestrial ingredients, the quantity of fish used to provide the marine ingredients reduces and hence the biotic resource use. The trade-off between biotic resource use and land use can clearly be seen in **Figure A.8.a** which shows the lower biotic resource use for terrestrial ingredients related to land transformation, compared to much higher land use (occupation). The relatively higher GWP of terrestrial ingredients is shown by the bubble size and the embodied fish within fishmeals is shown in **Figure A.8.b**.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Annex

Table A.1. Default boat construction and maintenance for purse seiner and trawler vessels

Input, per 1000MJ of fuel used	Purse Seiner		Trawler (Bottom, mid water, longline)	
Boat hull		SD95		SD95
Concrete (ballast), m^3	**6.41E-5**	1.29	**6.41E-5**	1.61
Steel (construction and maintenance), kg	**3.53**	3.27	**0.851**	4.7
Wood, m^3	**5.09E-4**	1.18	**5.09E-4**	1.5
Engine				
Cast iron, kg	**0.0479**	1.36	**0.0479**	1.66
Chromium steel, kg	**0.245**	1.36	**0.0536**	1.11
Aluminium alloy, kg	**7.37E-4**	1.36	**7.37E-4**	1.66
Copper, kg	**0.0292**	1.3	**0.131**	1.11
Net/ fishing gear				
Nylon, kg	**1.87**	8.34	**0.203**	6.17
Polyethylene, kg	**0.405**	9.1	**0.0228**	6.14
Lead, kg	**0.267**	3.22	**0.0152**	1.92
Paint (33% alkyd, 67% epoxy resin), kg	**0.251**	9.88	**0.0117**	1.68
Lubricating oil, kg	**0.247**	7.53	**0.0869**	1.22

[sources: Fréon *et al.* (2014), Ramos *et al.* (2011), Vasquez Rowe *et al*. (2013), Svanes *et al.* (2011), Vasquez Rowe *et al.* (2011), Vasquez Rowe *et al.* (2013), Fulton (2010). Uncertainty is shown as a lognormal SD95 value, as inputted into Simapro software; NB. data could not be found for all inputs and in such cases was deemed to be the same between purse seiners and trawlers although the NUSAP representativeness data was adjusted accordingly, resulting in higher uncertainty]

Table A.2. Antifouling emissions composition

Substance	Quantity
Arsenic, mg/kg	3.5
Copper, g/kg	341
Nickel, mg/kg	59.5
Lead, mg/kg	349
Tin, mg/kg	390
Zinc, g/kg	96.2
Tributyltin (TBT), mg/kg	1.1
Diphenyltin, mg/kg	5.7
Dibutyltin, mg/kg	0.9
Triphenyltin, mg/kg	17

[source, Fréon *et al.* (2014)]

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.3. Anchoveta fishery, Peru. Inputs and outputs per tonne of anchoveta landed

	Quantity	SD95
INPUTS		
Boat hull		
Concrete (ballast), m^3	4.25E-5	1.28
Steel (construction and maintenance), kg	2.213	1.12
Wood, m^3	3.99E-4	1.19
Engine		
Cast iron, kg	0.0317	1.36
Chromium steel, kg	0.0166	1.36
Aluminium alloy, kg	4.88E-4	1.36
Copper, kg	2.31E-3	1.36
Net/ fishing gear		
Nylon, kg	0.520	1.53
Polyethylene, kg	0.171	1.53
Lead, kg	0.114	1.53
Paint (33% alkyd, 67% epoxy resin), kg	8.47E-3	2.48
Lubricating oil, kg	0.113	1.67
Diesel used (fuel intensity), MJ	663	1.14
Antifouling emissions, kg	0.0153	2.48
OUTPUTS		Allocation %
Anchoveta landed at port (PE)	1000 kg	100

[source: Fréon *et al.* (2014)]

Table A.4. Atlantic horse mackerel from purse seiners, Spain, per tonne horse mackerel

	Quantity	SD95
INPUTS		
Boat hull		
Steel (construction and maintenance), kg	2.7	1.61
Net/ fishing gear		
Nylon, kg	6.53	2.47
Polyethylene, kg	2.14	2.47
Lead, kg	1.43	2.47
Chromium steel, kg	0.102	2.47
Paint (33% alkyd, 67% epoxy resin), kg	0.113	1.81
Lubricating oil, kg	0.447	2.04
Ice, kg	321	2.21
Diesel used (fuel intensity), MJ	7515	2.35
Antifouling emissions, kg	0.356	1.44
Refrigerant R22, kg	0.023	1.11
OUTPUTS		Allocation %
Atlantic horse mackerel landed at port (Spain), kg	1000	28.4
Atlantic mackerel landed at port (Spain), kg	1148	19.8
Sardine landed at port (Spain), kg	2009	51.9

[source: Vasquez-Rowe *et al.* (2011)]

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.5. Atlantic horse mackerel from bottom trawlers Spain, per tonne horse mackerel

	Quantity	SD95
INPUTS		
Boat hull		
Steel (construction and maintenance), kg	5.10	1.66
Net/ fishing gear		
Nylon, kg	1.56	1.88
Polyethylene, kg	0.504	1.88
Lead, kg	0.336	1.88
Chromium steel, kg	0.024	1.88
Paint (33% alkyd, 67% epoxy resin), kg	0.0743	1.55
Lubricating oil, kg	2.20	2.45
Ice, kg	323	1.67
Diesel used (fuel intensity), MJ	21179	1.53
Antifouling emissions, kg	0.639	1.34
Refrigerant R22, kg	0.222	1.11
OUTPUTS		**Allocation %**
Atlantic horse mackerel landed at port (Spain), kg	1000	14.7
Atlantic mackerel landed at port (Spain), kg	1193	10.7
Blue whiting landed at port (Spain), kg	2437	34.9
European hake landed at port (Spain), kg	991	39.7

[Vasquez-Rowe *et al.* (2011)]

Table A.6. Atlantic mackerel and sardine from North-East Atlantic Mackerel (NEAM) fishery, Spain, per tonne mackerel and sardine

	Quantity	SD95
INPUTS		
Boat hull		
Steel (construction and maintenance), kg	2.558	1.61
Net/ fishing gear		
Nylon, kg	1.94	1.62
Polyethylene, kg	0.636	1.60
Lead, kg	0.424	1.55
Chromium steel, kg	0.0303	1.60
Paint (33% alkyd, 67% epoxy resin), kg	0.345	1.56
Lubricating oil, kg	0.544	3.84
Ice, kg	124	1.11
Diesel used (fuel intensity), MJ	916	3.84
Antifouling emissions, kg	0.973	1.11
OUTPUTS		**Allocation %**
Atlantic mackerel from NEAM fishery landed at port (Spain), kg	919	88.2
Sardine from NEAM fishery landed at port (Spain), kg	81.0	11.8

[source: Ramos *et al.* (2011)]

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.7. Indian oil sardine, beach seine fishery, Oman

	Quantity	SD95
INPUTS		
Net/ fishing gear		
Nylon, kg	1.26	2.29
Polyethylene, kg	0.309	1.62
Polypropylene, kg	0.417	1.71
Lead, kg	0.819	3.26
Ethylene vinyl acetate (float), kg	0.317	1.58
OUTPUTS		**Allocation %**
Indian oil sardine landed on beach (Oman), kg	1000	100

[source: Das & Edwin (2016)]

Table A.8. Antarctic krill fishery, Uruguay, per tonne krill

	Quantity	SD95
INPUTS		
Boat hull and gears		
Steel (construction and maintenance), kg	3.69	1.11
Copper, kg	0.078	1.11
Polyethylene, kg	0.025	1.11
Rubber, kg	0.019	1.11
Diesel used (fuel intensity), MJ	3430	1.27
OUTPUTS		**Allocation %**
Krill landed on boat, kg*	1000	100

[source: Parker & Tydmers (2012)] * Krill is harvested and then processed in to meal, oil and paste on board

Table A.9. Longline mixed fishery, Iceland, per tonne mixed fish

	Quantity	SD95
INPUTS		
Boat hull		
Steel (construction and maintenance), kg	4.83	1.21
Net/ fishing gear		
Nylon, kg	1.87	1.11
Chromium steel, kg	0.09	1.11
Bait		
European squid, kg	39.3	1.14
Atlantic mackerel, kg	26.2	1.11
Diesel used (fuel intensity), MJ	2459	1.11
Antifouling emissions, kg	0.13	1.56
OUTPUTS		**Allocation %**
Cod from long-line fishery landed at port (Iceland), kg	550	61.0
Haddock from long-line fishery landed at port (Iceland), kg	160	15.7
Atlantic wolfish from long-line fishery landed at port (Iceland), kg	110	9.70
Ling from long-line fishery landed at port (Iceland), kg	70	6.90
Tusk from long-line fishery landed at port (Iceland), kg	50	2.65
Starry ray from long-line fishery landed at port (Iceland), kg	20	1.75
Spotted wolfish from long-line fishery landed at port (Iceland), kg	10	0.90
Redfish from long-line fishery landed at port (Iceland), kg	10	0.80
Saithe from long-line fishery landed at port (Iceland), kg	10	0.60

[source: Fulton (2010)]

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.10. Autoline mixed fishery, Norway, per tonne mixed fish

	Quantity	SD95
Net/ fishing gear		
Nylon, kg	0.65	1.11
Chromium steel, kg	0.97	1.11
Polypropylene, kg	1.30	1.11
Bait		
Atlantic herring, kg	17.0	1.11
Atlantic mackerel, kg	13.0	1.11
Diesel used (fuel intensity), MJ	10402	1.11
Antifouling emissions, kg	0.03	1.52
Paint (33% alkyd, 67% epoxy resin), kg	0.09	1.12
OUTPUTS		**Allocation %**
Cod from autoline fishery landed at port (Norway), kg	357	41.0
Haddock from autoline fishery landed at port (Norway), kg	258	26.2
Atlantic wolfish from autoline fishery landed at port (Norway), kg	19.2	1.8
Ling from autoline fishery landed at port (Norway), kg	91.0	9.3
Tusk from autoline fishery landed at port (Norway), kg	164	9.1
Atlantic halibut from autoline fishery landed at port (Norway), kg	19.2	5.1
Spotted wolfish from autoline fishery landed at port (Norway), kg	19.2	1.8
Redfish from autoline fishery landed at port (Norway), kg	19.2	1.6
Saithe from autoline fishery landed at port (Norway), kg	19.2	1.2

[source: Svanes et al. (2011)]

Table A.11. Norwegian mixed fisheries

NORWEGIAN COASTAL TRAWLER FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	5551	1.21
Trawler, vessel construction and maintenance per MJ	5551	1.13
Antifouling emissions	0.13	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from coastal fishery landed at port (Norway)	582	
Herring from coastal fishery landed at port (Norway)	153	72.5
Mackerel from coastal fishery landed at port (Norway)	18.4	6.20
Saithe from coastal fishery landed at port (Norway)	143	1.10
Haddock from coastal fishery landed at port (Norway)	103	9.50
		10.70
NORWEGIAN COASTAL SEINER FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	2989	1.21
Trawler, vessel construction and maintenance per MJ	2989	1.13
Antifouling emissions	0.015	1.56
Refrigerant R22	0.03	1.21

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

OUTPUTS Cod from coastal fishery landed at port (Norway) Herring from coastal fishery landed at port (Norway) Mackerel from coastal fishery landed at port (Norway) Saithe from coastal fishery landed at port (Norway) Haddock from coastal fishery landed at port (Norway)	 94.3 564 201 131 10.3	**Allocation %**
NORWEGIAN PELAGIC TRAWLER FISHERY **INPUTS** Diesel used (fuel intensity), MJ Trawler, vessel construction and maintenance per MJ Antifouling emissions Refrigerant R22	 3416 3416 0.015 0.03	**SD95** 1.21 1.13 1.56 1.21
OUTPUTS Herring from coastal seiner fishery landed at port (Norway) Mackerel from coastal seiner fishery landed at port (Norway) Saithe from coastal seiner fishery landed at port (Norway)	 779 183 38.7	**Allocation %** 70.7 23.6 5.7
NORWEGIAN COD TRAWLER FISHERY **INPUTS** Diesel used (fuel intensity), MJ Trawler, vessel construction and maintenance per MJ Antifouling emissions Refrigerant R22	 15372 15372 0.13 0.03	**SD95** 1.21 1.13 1.56 1.21
OUTPUTS Cod from cod trawler fishery landed at port (Norway) Saithe from cod trawler fishery landed at port (Norway) Haddock from cod trawler fishery landed at port (Norway)	 504 299 197	**Allocation %** 60.8 19.3 19.9
NORWEGIAN PURSE SEINER FISHERY **INPUTS** Diesel used (fuel intensity), MJ Purse seiner, vessel construction and maintenance per MJ Antifouling emissions Refrigerant R22	 4270 4270 0.015 0.03	**SD95** 1.21 1.13 1.56 1.21
OUTPUTS Cod from purse seiner fishery landed at port (Norway) Herring from purse seiner fishery landed at port (Norway) Mackerel from purse seiner fishery landed at port (Norway) Saithe from purse seiner fishery landed at port (Norway)	 9.0 650 343 6.0	**Allocation %** 0.2 56.5 42.4 0.9
NORWEGIAN OCEAN FISHERY **INPUTS** Diesel used (fuel intensity), MJ Trawler, vessel construction and maintenance per MJ Antifouling emissions Refrigerant R22	 10248 10248 0.13 0.03	**SD95** 1.21 1.13 1.56 1.21

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

OUTPUTS		Allocation %
Cod from ocean fishery landed at port (Norway)	611	67.3
Saithe from ocean fishery landed at port (Norway)	94.7	5.6
Haddock from ocean fishery landed at port (Norway)	294	27.1

[source: SINTEF (2020)]

Table A.12. Contribution of different Norwegian fisheries to total catch per species

Species \ Fishery	Coastal trawler	Ocean trawler	Cod trawler	Coastal seiner	Purse seiner	Pelagic trawler
Atlantic cod	51.0	8.60	35.2	4.80	0.10	-
Haddock	32.7	15.0	49.9	1.90	-	-
Saithe	29.1	3.10	48.5	15.5	1.60	1.30
Atlantic herring	10.5	-	-	22.5	58.3	8.80
Atlantic mackerel	3.0	-	-	19.0	73.1	4.90

[source: SINTEF (2020)]

Table A.13. Danish mixed fisheries

DANISH COD FISHERY		SD95
INPUTS		
Diesel used (fuel intensity), MJ	14404	1.21
Trawler, vessel construction and maintenance per MJ	14404	1.13
Antifouling emissions	0.13	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from cod fishery landed at port (Denmark)	697	80.2
Flatfish from cod fishery landed at port (Denmark)	80.8	12.2
Norway lobster from cod fishery landed at port (Denmark)	1.40	0.7
Herring from cod fishery landed at port (Denmark)	130	4.8
Mackerel from cod fishery landed at port (Denmark)	16.5	0.6
Sandeel from cod fishery landed at port (Denmark)	64.5	0.7
Mixed fish from cod fishery landed at port (Denmark)	8.90	0.8
DANISH COD/FLATFISH FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	14807	1.21
Trawler, vessel construction and maintenance per MJ	14807	1.13
Antifouling emissions	0.18	1.56
Refrigerant R22	0.03	1.21

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

OUTPUTS		**Allocation %**
Cod from cod/flatfish fishery landed at port (Denmark)	473	53.2
Flatfish from cod/flatfish fishery landed at port (Denmark)	290	42.6
Norway lobster from cod/flatfish fishery landed at port (Denmark)	1.50	0.81
Herring from cod/flatfish fishery landed at port (Denmark)	1.69	0.06
Mackerel from cod/flatfish fishery landed at port (Denmark)	0.21	0.01
Sandeel from cod/flatfish fishery landed at port (Denmark)	221	2.25
Mixed fish from cod/flatfish fishery landed at port (Denmark)	12.4	1.17
DANISH FLATFISH FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	37390	1.21
Trawler, vessel construction and maintenance per MJ	37390	1.13
Antifouling emissions	0.18	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from flatfish fishery landed at port (Denmark)	132	11.1
Flatfish from flatfish fishery landed at port (Denmark)	788	87.0
Norway lobster from flatfish fishery landed at port (Denmark)	0.50	0.20
Sandeel from flatfish fishery landed at port (Denmark)	62.1	0.50
Mixed fish from flatfish fishery landed at port (Denmark)	17.3	1.20
DANISH INDUSTRIAL FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	2504	1.21
Purse seiner, vessel construction and maintenance per MJ	2504	1.13
Antifouling emissions	0.01	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from industrial fishery landed at port (Denmark)	1.3	1.3
Flatfish from industrial fishery landed at port (Denmark)	0.3	0.5
Herring from industrial fishery landed at port (Denmark)	26.0	8.3
Mackerel from industrial fishery landed at port (Denmark)	3.28	1.0
Sandeel from industrial fishery landed at port (Denmark)	969	88.6
Mixed fish from industrial fishery landed at port (Denmark)	0.3	0.2
DANISH PELAGIC FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	3910	1.21
Purse seiner, vessel construction and maintenance per MJ	3910	1.13
Antifouling emissions	0.015	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from pelagic fishery landed at port (Denmark)	2.40	1.2
Herring from pelagic fishery landed at port (Denmark)	426	66.9
Mackerel from pelagic fishery landed at port (Denmark)	53.7	8.4
Sandeel from pelagic fishery landed at port (Denmark)	528	23.4
Norway lobster from pelagic fishery landed at port (Denmark)	0.03	0.1

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

DANISH MIXED FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	5060	1.21
Purse seiner, vessel construction and maintenance per MJ	5060	1.13
Antifouling emissions	0.1	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from mixed fishery landed at port (Denmark)	40.4	9.0
Flatfish from mixed fishery landed at port (Denmark)	20.1	5.8
Norway lobster from mixed fishery landed at port (Denmark)	3.30	3.4
Herring from mixed fishery landed at port (Denmark)	103	7.2
Mackerel from mixed fishery landed at port (Denmark)	13.0	0.9
Sandeel from mixed fishery landed at port (Denmark)	520	10.5
Mixed fish from mixed fishery landed at port (Denmark)	299	63.2
DANISH NORWAY LOBSTER FISHERY		**SD95**
INPUTS		
Diesel used (fuel intensity), MJ	60010	1.21
Purse seiner, vessel construction and maintenance per MJ	60010	1.13
Antifouling emissions	0.23	1.56
Refrigerant R22	0.03	1.21
OUTPUTS		**Allocation %**
Cod from Norway lobster fishery landed at port (Denmark)	298	18.9
Flatfish from Norway lobster fishery landed at port (Denmark)	167	13.9
Norway lobster from Norway lobster fishery landed at port (Denmark)	194	57.7
Herring from Norway lobster fishery landed at port (Denmark)	29.7	0.6
Mackerel from Norway lobster fishery landed at port (Denmark)	3.70	0.1
Sandeel from Norway lobster fishery landed at port (Denmark)	170	1.0
Norway lobster fish from Norway lobster fishery landed at port (Denmark)	138	7.9

[source: Thrane (2004)]

Table A.14. Contribution of different Danish fisheries to total catch per species, percent

Fishery / Species	Cod fishery	Cod/ flatfish	Flatfish	Norway lobster	Pelagic	Industrial	Mixed fish
Atlantic cod	29.7	21.7	6.02	13.0	8.45	4.86	16.3
Flatfish	4.95	19.2	51.8	10.5	0.12	1.83	11.7
Atlantic herring	3.3	-	-	0.08	91.4	5.74	2.49
Atlantic mackerel	3.3	-	-	0.08	91.4	5.74	2.49
Sandeel	0.05	0.18	0.05	0.13	32.8	63.0	3.71
Norway lobster	0.58	0.70	0.24	83.8	1.10	0.43	13.2
Mixed fish	0.1	0.12	7.15	3.14	0.01	0.50	96.2

[source: Thrane (2004)]

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.15 Other fishery data as available, all inputs are according to economic allocation to main species where given

Location	Species	Source	Gear type	Fuel intensity MJ*	Anti-fouling, kg	Other
Portugal	Sardine	Almeida et al 2014	PS	1138	0.025	ice – 45kg
Iceland	Blue whiting	Fisheries Iceland 2017	MW	3062	0.02	-
Iceland	Capelin	Fisheries Iceland 2017	PS	1044	0.02	-
Iceland	Herring	Fisheries Iceland 2017	PS	1044	0.02	-
Iceland	Atlantic mackerel	Fisheries Iceland 2017	MW	3062	0.02	-
Norway	Blue whiting	Schau et al 2009	MW	2135	0.02	-
Norway	Capelin	Schau et al 2009	PS	2135	0.02	-
Norway	European sprat	Schau et al 2009	PS	2135	0.02	-
Denmark	European sprat	Tyedmers 2004	PS	3371	0.02	-
USA	Gulf menhaden	Cashion et al 2016	PS	1162	0.03	-
Mexico	California pilchard	Cashion et al 2016	PS	3589	0.1	-

Table A.16. Anchoveta rendering per ton of anchoveta raw material

	Avadi et al 2014		Fréon et al 2017	
	Prime	Standard	Prime	Standard
INPUTS				
Heat (gas burned in furnace), MJ	1518	1965	356	454
Electricity use, KWh	20.6	13.7	4.89	3.28
Sodium hydroxide, kg	-	-	0.140	0.138
Sodium chloride, kg	-	-	0.0950	0.140
Antioxidant	-	-	0.0404	0.0594
Concrete infrastructure, kg	-	-	3.25	0.468
Metal infrastructure, kg	-	-	91.9	52.3
Copper wire, kg	-	-	1.24	0.670
Bags, kg	-	-	0.145	0.141
Emissions				
Total nitrogen, kg	0.131	0.131	-	-
Total phosphorous, kg	0.00119	0.00119	-	-
BOD/ COD	9.17	17.8	2.18	4.23
Suspended solids	-	-	0.879	1.64
OUTPUTS				
Fishmeal	238	238	238	238
Fish oil	45.1	45.1	45.1	45.1

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.17. Sandeel rendering per tonne of sandeel raw material

INPUTS	
Heat (gas burned in furnace), MJ	1330
Electricity use, KWh	40.8
Sodium hydroxide, kg	1.03
Sulphuric acid, kg	0.451
Nitric acid, kg	0.116
Formalin, kg	2.318
Antioxidant, kg	0.0663
Emissions	
Total nitrogen, kg	0.236
Total phosphorous, kg	0.001665
BOD/ COD	0.966
	-
OUTPUTS	
Fishmeal	215
Fish oil	45.1

[source: Danish LCA food database[14]]

Table A.18. Default rendering inventory per tonne raw material

INPUTS		
Heat (gas burned in furnace), MJ	1140	4.65
Electricity use, KWh	12.1	7.91
Sodium hydroxide, kg	0.448	10.1
Sodium chloride, kg	0.118	1.73
Formalin, kg	0.0551	1.11
Antioxidant, kg	0.0515	1.68
Copper wire, kg	0.958	2.24
Bags, kg	0.143	1.11
Emissions		
Total nitrogen, kg	0.141	1.98
Total phosphorous, kg	0.00171	7.29
BOD/ COD, kg	7.98	9.98
Suspended solids, kg	1.26	2.42

[sources: Avadi *et al.* (2014), Fréon *et al.* (2017), Danish LCA food database]

[14] http://www.lcafood.dk/

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.19. Economically allocated Life Cycle Impact Assessment of 1 tonne of key fishmeal resources used in European aquaculture

	GWP	AP	EP	ODP	POP	CWU	BRU	eFIFO
	kg CO_2eq	kg SO_2eq	kg PO_4eq	kg CFC11eq	kg C_2H_4eq	M^3	kg C	kg Fish In
WHOLE FISH MEALS								
Anchoveta (*Engraulis ringens*) FAQ (PE)	658	7.48	0.88	1.13E-4	0.244	2.08	3.09E4	3500
Anchoveta (*Engraulis ringens*) prime (PE)	486	4.78	0.77	5.91E-5	0.141	1.71	3.09E4	3500
Blue whiting (*Micromesistius poutassou*) (IS)	1680	29.6	6.53	2.95E-4	0.788	5.06	6.44E5	4600
Blue whiting (*Micromesistius poutassou*) (NO)	1290	21.2	5.26	2.24E-4	0.577	4.50	6.44E5	4600
Capelin (*Mallotus villosus*) (IS)	821	10.2	3.34	1.24E-4	0.307	4.46	7.12E4	4040
Capelin (*Mallotus villosus*) (NO)	1320	19.1	4.68	1.98E-4	0.545	7.69	7.12E4	4040
Atlantic herring (*Clupea harengus*) (IS)	590	7.34	2.40	8.91E-5	0.221	3.20	8.11E4	2910
Atlantic herring (*Clupea harengus*) (NO)	1270	19.7	4.27	2.17E-4	0.550	7.19	8.11E4	2910
Atlantic herring (*Clupea harengus*) (DK)	2300	37.5	7.00	5.07E-4	1.03	12.7	8.11E4	2910
Atlantic mackerel (*Scomber scombrus*) (IS)	1100	16.8	3.67	1.65E-4	0.471	6.39	1.13E5	2540
Atlantic mackerel (*Scomber scombrus*) (NO)	1580	25.4	4.98	2.60E-4	0.703	9.11	1.13E5	2540
Atlantic mackerel (*Scomber scombrus*) (DK)	2000	32.6	6.09	4.41E-4	0.897	11.1	1.13E5	2540
Atlantic mackerel (*Scomber scombrus*) (ES)	535	7.05	2.15	9.94E-5	0.205	2.12	1.13E5	2540
Atlantic horse mackerel (*Trachurus trach.*) (ES)	1150	19.0	4.16	2.77E-4	0.506	4.10	1.89E5	3400
Sardine (*Sardina pilchardus*) (ES)	654	9.66	2.43	1.19E-4	0.267	3.19	3.31E4	2370
Sardine (*Sardina pilchardus*) (PT)	529	6.62	2.07	7.95E-5	0.199	3.07	3.31E4	2370
European sprat (*Sprattus sprattus*) (NO)	1200	17.3	4.25	1.80E-4	0.495	6.98	4.08E4	3670
European sprat (*Sprattus sprattus*) (DK)	1730	26.5	5.67	2.57E-4	0.742	9.32	4.08E4	3670
Sandeel (*Ammodytes marinus*) (DK)	1300	16.2	2.79	2.76E-4	0.454	7.51	5.32E4	3800
Indian oil sardine (*Sardinella longiceps*) (OM)	257	1.3	1.29	2.47E-5	0.0628	1.27	6610	2370
Gulf menhaden (*Brevoortia patronus*) (US)	589	7.36	2.33	7.86E-5	0.224	2.49	4620	2620
California pilchard (*Sardinops sagax*) (PA)	1180	18.2	3.83	1.67E-4	0.513	6.07	1.66E4	2370
Krill (*Euphausia superba*)	4190	56.4	10.2	6.15E-4	1.87	14.4	1.18E4	6690
BY-PRODUCT MEALS								
Atlantic herring (*Clupea harengus*) (IS)	371	2.32	1.47	4.33E-5	0.0878	5.31	1.29E4	461
Atlantic herring (*Clupea harengus*) (NO)	474	4.27	1.77	6.38E-5	0.140	6.80	1.29E4	461
Atlantic herring (*Clupea harengus*) (DK)	679	7.24	2.30	1.12E-4	0.222	5.92	1.29E4	461
Atlantic mackerel (*Scomber scombrus*) (IS)	469	4.11	1.74	5.83E-5	0.136	5.79	1.98E4	449
Atlantic mackerel (*Scomber scombrus*) (NO)	550	5.63	1.97	7.54E-5	0.176	7.15	1.98E4	449
Atlantic mackerel (*Scomber scombrus*) (DK)	664	7.04	2.27	1.09E-4	0.216	5.77	1.98E4	449
Mixed white fish (cod, haddock etc) (IS)	973	8.19	3.68	1.30E-4	0.273	15.8	9.05E4	907
Mixed white fish (cod, haddock etc) (NO)	1450	19.8	5.42	2.23E-4	0.559	20.8	1.25E5	852
Mixed white fish (cod, haddock etc) (DK)	2340	33.7	7.87	4.00E-4	0.937	17.2	1.36E5	852
Mixed white fish (cod, haddock etc) (UK)	1580	18.1	5.36	2.21E-4	0.537	7.43	1.26E5	867

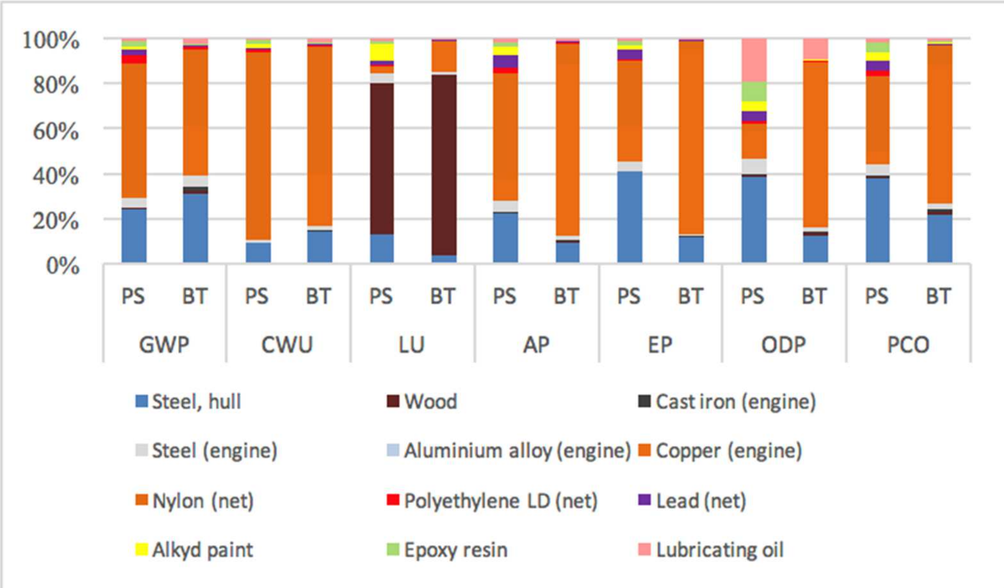
The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Table A.20. Economically allocated Life Cycle Impact Assessment of 1 tonne of key fish oil resources used in European aquaculture

	GWP	AP	EP	ODP	POP	CWU	BRU	eFIFO
	kg CO_2eq	kg SO_2eq	kg PO_4eq	kg CFC11eq	kg C_2H_4eq	M^3	kg C	kg Fish In
WHOLE FISH OILS								
Anchoveta (*Engraulis ringens*) FAQ (PE)	705	8.01	0.942	1.21E-4	0.262	2.22	3.31E4	3750
Anchoveta (*Engraulis ringens*) prime (PE)	521	5.12	0.826	6.33E-5	0.151	1.84	3.31E4	3750
Blue whiting (*Micromesistius poutassou*) (IS)	1800	31.7	6.99	3.16E-4	0.844	5.42	6.89E5	4930
Blue whiting (*Micromesistius poutassou*) (NO)	1380	22.7	5.63	2.40E-4	0.618	4.82	6.89E5	4930
Capelin (*Mallotus villosus*) (IS)	880	10.9	3.57	1.33E-4	0.329	4.77	7.62E4	4330
Capelin (*Mallotus villosus*) (NO)	1410	20.4	5.02	2.12E-4	0.584	8.24	7.62E4	4330
Atlantic herring (*Clupea harengus*) (IS)	632	7.87	2.57	9.54E-5	0.236	3.43	8.69E4	3110
Atlantic herring (*Clupea harengus*) (NO)	1360	21.1	4.58	2.33E-4	0.589	7.70	8.69E4	3110
Atlantic herring (*Clupea harengus*) (DK)	2460	40.1	7.49	5.43E-4	1.11	13.7	8.69E4	3110
Atlantic mackerel (*Scomber scombrus*) (IS)	1180	17.9	3.93	1.76E-4	0.504	6.61	1.20E5	2720
Atlantic mackerel (*Scomber scombrus*) (NO)	1690	27.2	5.34	2.79E-4	0.753	9.76	1.20E5	2720
Atlantic mackerel (*Scomber scombrus*) (DK)	2140	34.9	6.52	4.72E-4	0.960	11.9	1.20E5	2720
Atlantic mackerel (*Scomber scombrus*) (ES)	573	7.55	2.30	1.06E-4	0.219	2.27	1.2E5	2720
Atlantic horse mackerel (*Trachurus trachurus*) (ES)	1230	20.4	4.45	2.97E-4	0.542	4.39	2.03E5	3640
Sardine (*Sardina pilchardus*) (ES)	701	10.4	2.60	1.27E-4	0.286	3.42	3.54E4	2530
Sardine (*Sardina pilchardus*) (PT)	566	7.09	2.21	8.52E-5	0.213	3.29	3.54E4	2530
European sprat (*Sprattus sprattus*) (NO)	1280	18.6	4.55	1.93E-4	0.530	7.48	4.37E4	3930
European sprat (*Sprattus sprattus*) (DK)	1850	28.4	6.08	2.76E-4	0.795	9.98	4.37E4	3930
Sandeel (*Ammodytes marinus*) (DK)	1400	17.4	2.99	2.96E-4	0.487	8.05	5.70E4	4070
Indian oil sardine (*Sardinella longiceps*) (OM)	275	1.39	1.38	2.64E-5	0.0673	1.36	7.08E3	2540
Gulf menhaden (*Brevoortia patronus*) (US)	631	7.89	2.50	8.42E-5	0.240	2.67	4.95E3	2810
California pilchard (*Sardinops sagax*) (PA)	1270	19.5	4.10	1.79E-4	0.550	6.50	1.78E4	2530
Krill (*Euphausia superba*)	4470	60.2	10.9	6.57E-4	1.99	15.3	1.26E4	7140
BY-PRODUCT MEALS								
Atlantic herring (*Clupea harengus*) (IS)	397	2.49	1.58	4.64E-5	0.0940	5.69	1.38E4	493
Atlantic herring (*Clupea harengus*) (NO)	508	4.58	1.89	6.84E-5	0.149	7.29	1.38E4	493
Atlantic herring (*Clupea harengus*) (DK)	727	7.76	2.46	1.20E-4	0.238	6.34	1.38E4	493
Atlantic mackerel (*Scomber scombrus*) (IS)	503	4.40	1.87	6.24E-5	0.145	6.20	2.13E4	480
Atlantic mackerel (*Scomber scombrus*) (NO)	589	6.03	2.11	8.27E-5	0.189	7.66	2.13E4	480
Atlantic mackerel (*Scomber scombrus*) (DK)	712	7.54	2.43	1.17E-4	0.232	6.18	2.13E4	480
Mixed white fish (cod, haddock etc) (IS)	1040	8.77	3.94	1.30-4	0.292	17.0	9.68E4	971
Mixed white fish (cod, haddock etc) (NO)	1550	21.2	5.81	2.39E-4	0.599	22.3	1.34E5	912
Mixed white fish (cod, haddock etc) (DK)	2500	36.1	8.43	4.28E-4	1.00	18.5	1.46E5	912
Mixed white fish (cod, haddock etc) (UK)	1690	19.3	5.74	2.36E-4	0.575	7.96	1.35E5	928

[project results]

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330



(a)

GWP	PS	26.36033
kg CO_2eq	BT	4.988145
CWU	PS	0.51457
m^3	BT	0.081301
LU	PS	2.157819
m^2yr^{-1}	BT	1.815578
AP	PS	0.119111
kg SO_2eq	BT	0.067162
EP	PS	0.050038
kg PO_4eq	BT	0.042659
ODP	PS	8.41E-07
kg CFC-11eq	BT	6.35E-07
PCO	PS	0.007798
kg C_2H_4eq	BT	0.003323

(b)

Figures 7.3.a and 7.3.b – Contribution analysis to environmental impacts for default fishing activities, per 1000MJ of fishing effort. PS = Purse Seiner, BT = Bottom trawler, GWP – Global Warming Potential, CWU = Consumptive Water Use, LU = Land use, AP = Acidification potential, EP = Eutrophication potential, ODP = Ozone depletion potential, PCO = Photochemical oxidation potential

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

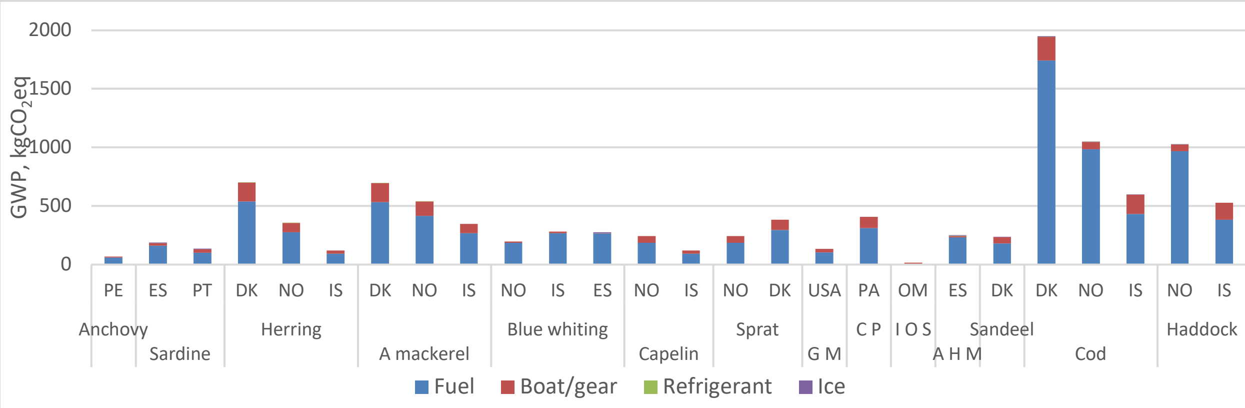


Figure A.2 – Global warming potential (GWP) contribution analysis for major fish species used in marine ingredients supplied to European aquaculture, pe tonne landed catch. G M = gulf menhaden, C P = California pilchard, I O S = Indian oil sardine, A H M = Atlantic horse mackerel, PE = Peru, ES = Spain, PT = Portugal, DK = Denmark, NO = Norway, IS = Iceland, PA = Panama, OM = Oman.

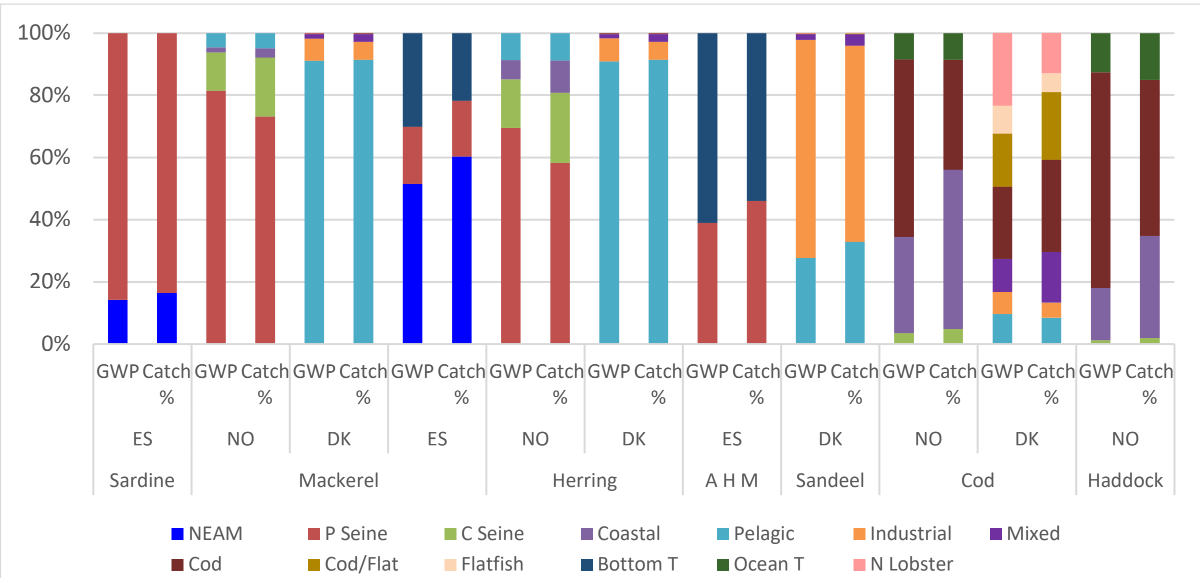


Figure A.3 – Contribution of different fishery types to national catches and GWP for major European marine ingredients species. ES = Spain, NO = Norway, DK = Denmark, NEAM = North East Atlantic Mackerel fishery, P Seine = purse seine, C seine = coastal seine, Bottom T = bottom trawl, Ocean T = ocean trawl, N lobster = Norwegian lobster. Fisheries are named according to the literature source.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

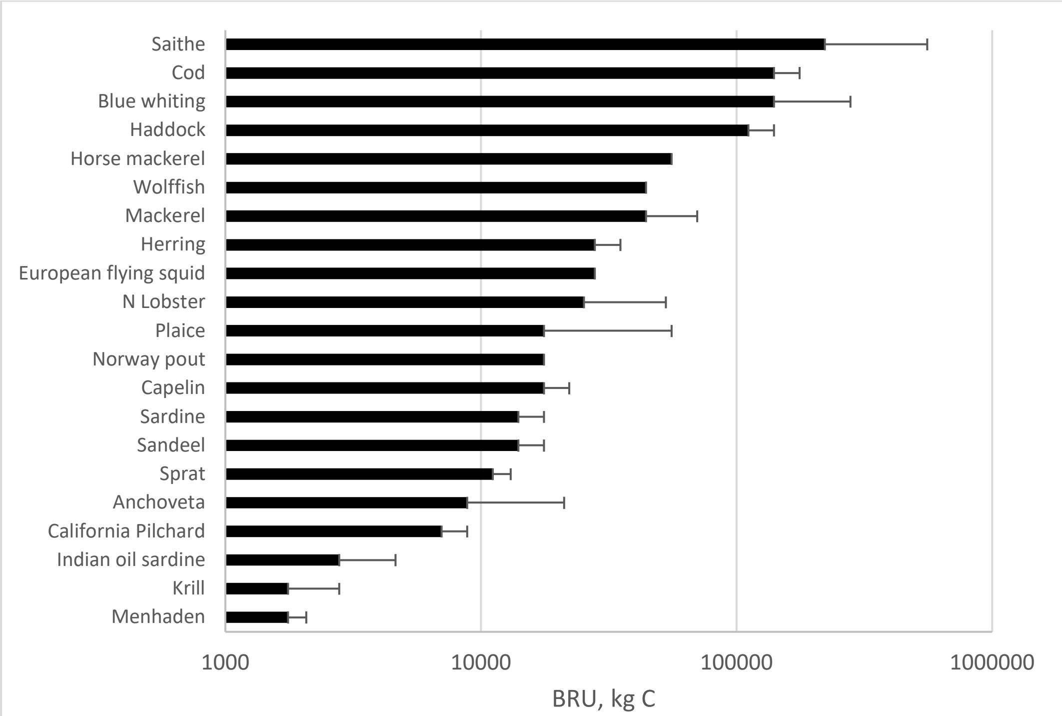


Figure A.4 – Biotic Resource Use (BRU), kg C per ton, for some major EU fisheries species

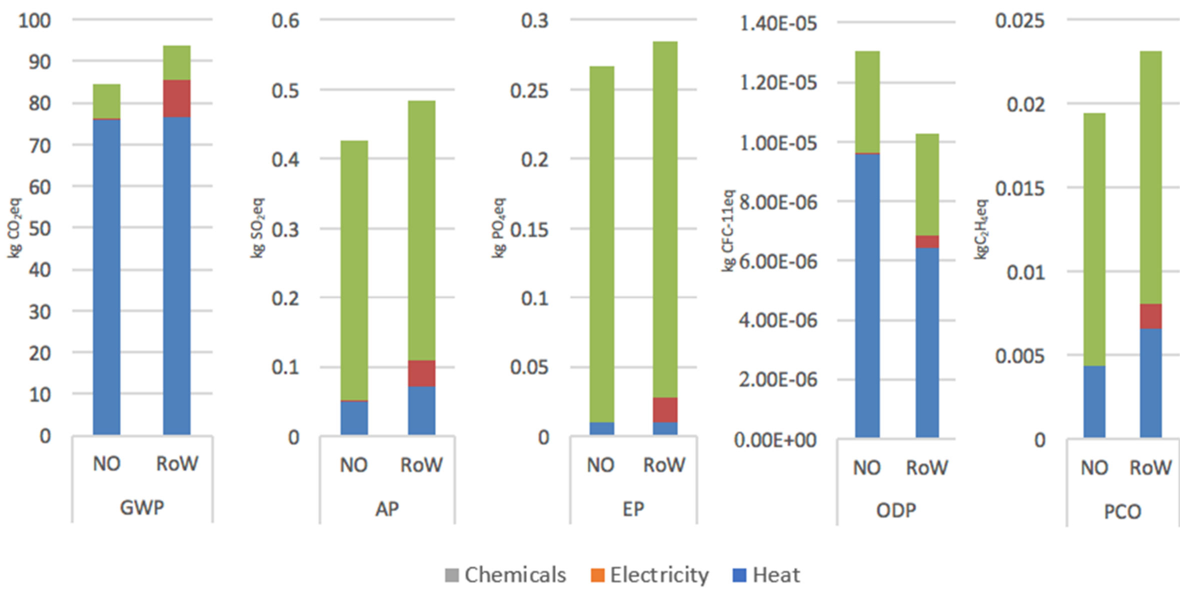


Figure A.5 – Default rendering emissions for Norway (NO) and Rest of the World (RoW) per ton of raw material rendered.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

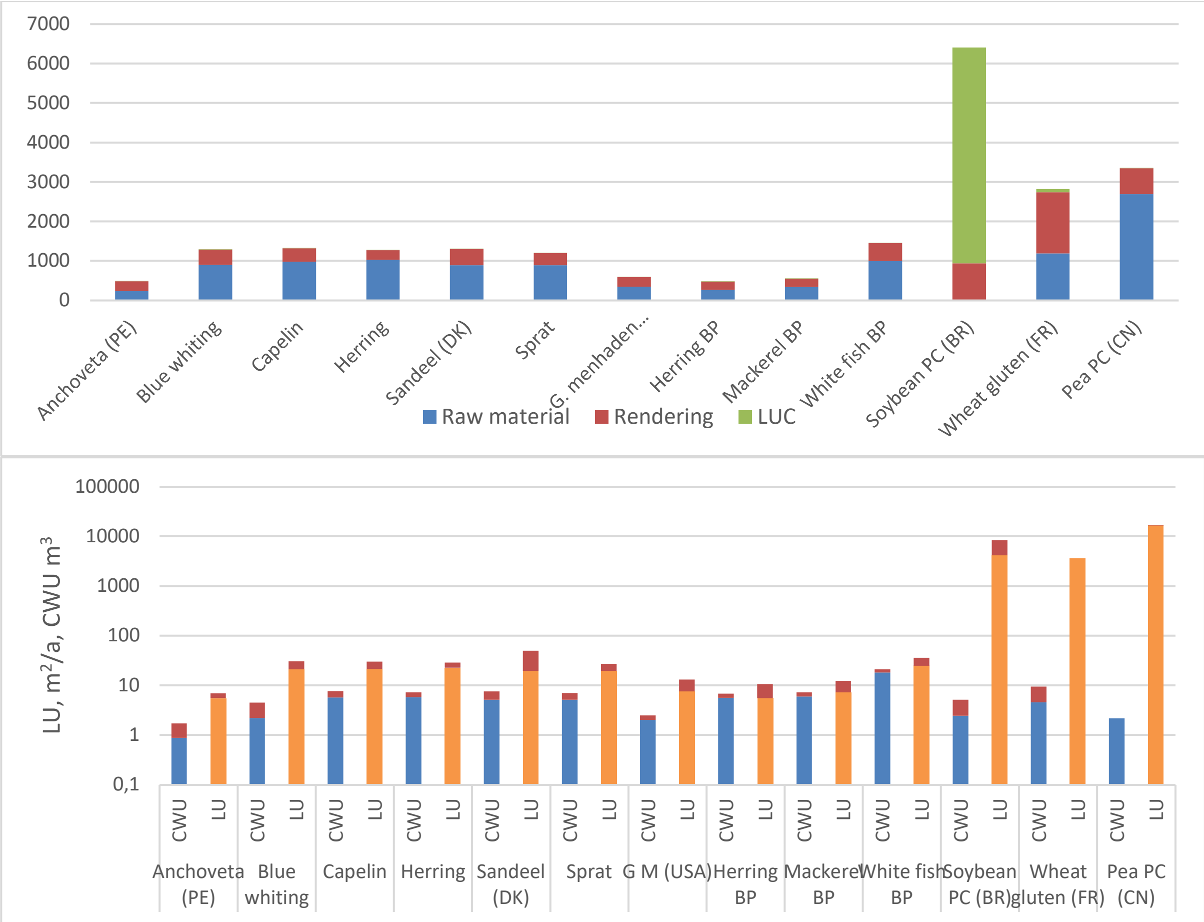


Figure A.6.a – GWP contributions for selected fishmeals and plant proteins per tonne of meal. All fishmeals from Norway unless otherwise stated. PE = Peru, DK = Denmark, BR = Brazil, FR = France, CN = China, BP = by-product, and

Figure A.6.b – Consumptive Water Use and Land Use for selected fishmeal and plant proteins per tonne. Blue/green = raw material, orange = rendering contributions. G M = Gulf menhaden, PC = protein concentrate.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

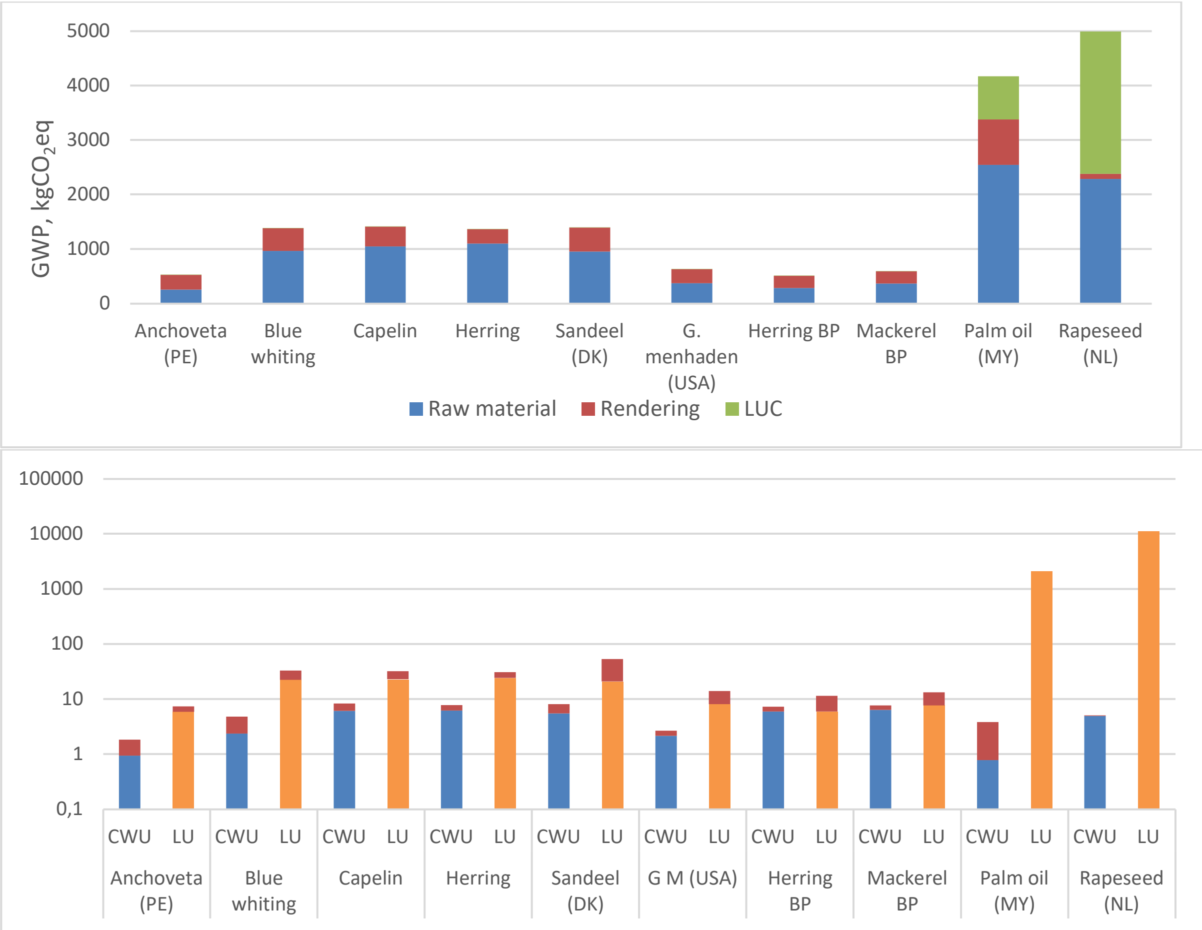


Figure A.7.a – GWP contributions for selected fish and plant oils per tonne. All fish oils from Norway unless otherwise stated. PE = Peru, DK = Denmark, MY = Malaysia, NL = Netherlands, BP = by-product, and **Figure A.7.b** – Consumptive Water Use and Land Use for selected fishmeal and plant proteins per tonne. Blue/green = raw material, orange = rendering contributions. GM = Gulf Menhaden.

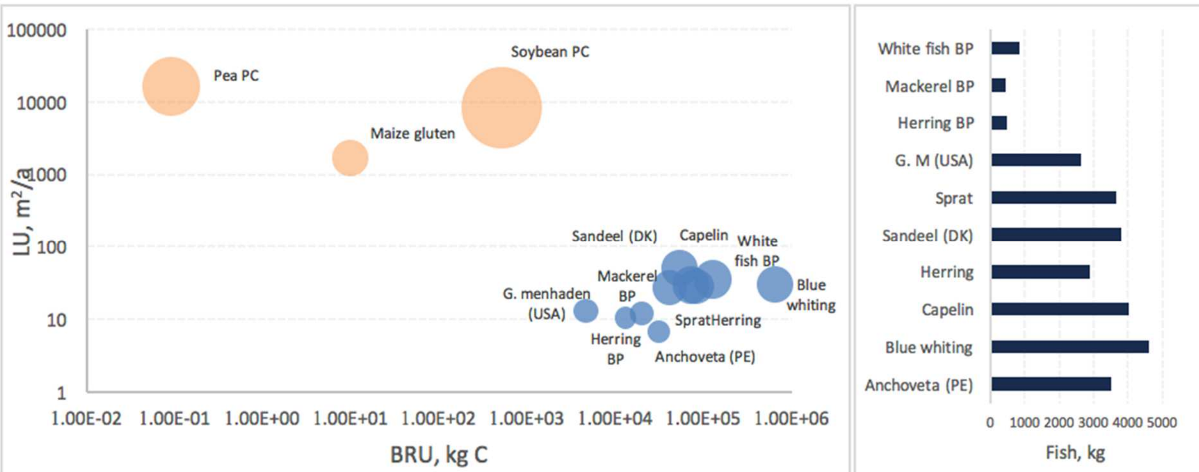


Figure A.8.a – Land Use (LU) and Biotic Resource Use (BRU) for selected terrestrial (green) and marine (blue) protein ingredients used in aquafeeds. Size of bubble denotes relative GWP and **Figure A.8.b** – embodied fish within selected marine ingredients from Norway unless otherwise stated. GM = gulf menhaden.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

References

Agri-footprint (2015). Blonk Agri-footprint BV. Agri-Footprint Version 3.0. Gouda, the Netherlands.

Almeida, C., Vaz, S., Cabral, H. & Ziegler, F. (2013). Environmental assessment of sardine (Sardina pilchardus) purse seine fishery in Portugal with LCA methodology including biological impact categories. *The International Journal of Life Cycle Assessment, 19*, 297-306.

ASC (2017). ASC Salmon Standard v1.1 - April 2017. Aquaculture Stewardship Council. 103 pp.

Avadí, Á., Vázquez-Rowe, I. & Fréon, P. (2014). Eco-efficiency assessment of the Peruvian anchoveta steel and wooden fleets using the LCA+DEA framework. *Journal of Cleaner Production, 70*, 118-131.

Baarset, H. (2021). End-of-life scenarios for the dried products derived from aquaculture side-streams. Waister. Memo for partners' internal use dated 03 March 2021.

Baaeset, H., & Johansen, J. (2019). Innovative processes for mortality disposal in aquaculture. Deliverable 2.2. GAIN – Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 773330. 14pp.

Baarset, H., Bruckner, C., Cristiano, S., Kreiss, K. (2021). Eco-efficient disposal of aquaculture mortalities. Deliverable 2.6. GAIN – Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 773330.

Barros, M. C., Bello, P. M., Bao, M., & Torrado, J. J. (2009). From waste to commodity: transforming shells into high purity calcium carbonate. *Journal of Cleaner Production*, *17*(3), 400-407.

Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2019). Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture*, *11*(4), 1061-1079.

Bohnes, F. A., & Laurent, A. (2019). LCA of aquaculture systems: methodological issues and potential improvements. *The International Journal of Life Cycle Assessment*, *24*(2), 324-337.

Bolzonella, M., Royer, E., & Pastres, R. (2021). An individual-based bioenergetic model of rainbow trout (*Onchorhynchus mykiss*). *Aquaculture Europe 2020.* Book of abstracts.

Bösch, M. E., Hellweg, S., Huijbregts, M. A., & Frischknecht, R. (2007). Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. *The International Journal of Life Cycle Assessment*, *12*(3), 181-190.

Boyd, C. E., Torrans, E. L., & Tucker, C. S. (2018). Dissolved oxygen and aeration in ictalurid catfish aquaculture. *Journal of the World Aquaculture Society*, *49*(1), 7-70.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Bregnballe, J. (2015). *Recirculation Aquaculture. An introduction to the new environmentally friendly and highly productive closed fish farming systems*. www.fao.org/3/a-i4626e.pdf

Broadbent, C. (2016). Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *The International Journal of Life Cycle Assessment*, *21*(11), 1658-1665.

Bruckner, C., Johansen, J., Ferreira Novio, M., Svenningson, L., Baarset, H., Conceição, L., & Soula, M. (2021). Eco-efficient solutions for reusing aquaculture side stream. Deliverable 2.5. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 77330.

Cashion, T., Hornborg, S., Ziegler, F., Hognes, E. S. & Tyedmers, P. (2016) Review and advancement of the marine biotic resource use metric in seafood LCAs: a case study of Norwegian salmon feed. *The International Journal of Life Cycle Assessment, 21*, 1106-1120.

Cashion, T., Tyedmers, P. & Parker, R. W. R. (2017). Global reduction fisheries and their products in the context of sustainable limits. *Fish and Fisheries, 18*, 1026-1037.

Castiglione, E., Del Bravo, F., & Carbonari, F. (2009). Acquacoltura. Report economico finanziario. Istituto di Servizi per il Mercato Agricolo Alimentare.

Das, D. P. H. & Edwin, L. (2016). Comparative Environmental Life Cycle Assessment of Indian Oil sardine Fishery of Kerala, India. *Fishery Technology, 53*, 273-283.

European Commission (2019). Life Cycle Assessment of the environmental impacts of the bioeconomy. *The European Commission's science and knowledge service*. [https://ec.europa.eu/jrc/en/science-update/life-cycle-assessment-environmental-impacts-bioeconomy, retrieved 07 May 2021].

Ewing B., D. Moore, S. Goldfinger, A. Oursler, A. Reed, & M. Wackernagel (2010). *The Ecological Footprint Atlas 2010*. Oakland: Global Footprint Network.

FAO (1989). Yield and Nutritional Value of the Commercially More Important Fish Species. *FAO Fisheries Technical Paper*. No. 309. FAO, Rome. 187 pp.

FAO (2019). Fisheries and aquaculture software. FishStat Plus - Universal software for fishery statistical time series. In: FAO. *Fisheries and Aquaculture Department* [online]. Rome.

Fishbase.org (2021). FishBase. World Wide Web electronic publication. www.fishbase.org, (02/2021). (Eds R. Froese & D. Pauly).

Fisheries Iceland (2017). Resource Utilisation and Environmental Footprint. 32 pp.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., ... & Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. Chapter 2. In *Climate Change 2007. The Physical Science Basis*.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Fréon, P., Avadí, A., Vinatea Chavez, R. A. & Iriarte Ahón, F. (2014). Life cycle assessment of the Peruvian industrial anchoveta fleet: boundary setting in life cycle inventory analyses of complex and plural means of production. *The International Journal of Life Cycle Assessment, 19*, 1068-1086.

Fréon, P., Durand, H., Avadí, A., Huaranca, S. & Orozco Moreyra, R. (2017). Life cycle assessment of three Peruvian fishmeal plants: Toward a cleaner production. *Journal of Cleaner Production, 145*, 50-63.

Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., ... & Berckmans, D. (2018). Precision fish farming: A new framework to improve production in aquaculture. *Biosystems Engineering*, *173*, 176-193.

Frischknecht, R., Jungbluth, N., Althaus, H. J., Hischier, R., Doka, G., Dones, R., ... & Spielmann, M. (2007). *Overview and methodology. Data v2. 0 (2007). Ecoinvent report No. 1* (No. INIS-CH--10089). Ecoinvent Centre.

Fulton, S. (2010). Fish and Fuel: Life cycle greenhouse gas emissions associated with Icelandic cod, Alaskan pollock, and Alaskan pink salmon fillets delivered to the United Kingdom.

GAA (2016). Aquaculture Facility Certification, Salmon Farms, Best Aquaculture Practices Certification Standards, Guidelines. Global Aquaculture Alliance. 23 pp.

GlobalGAP (2019). Integrated Farm Assurance. 99 pp. Available from: https://www.globalgap.org/uk_en/for-producers/globalg.a.p./integrated-farm-assurance-ifa/aquaculture/.

Henriksson, P. J., Guinée, J. B., Kleijn, R., & de Snoo, G. R. (2012). Life cycle assessment of aquaculture systems—a review of methodologies. *The International Journal of Life Cycle Assessment*, *17*(3), 304-313.

Henriksson, P. J. G., Guinée, J. B., Heijungs, R., de Koning, A. & Green, D. M. (2013). A protocol for horizontal averaging of unit process data—including estimates for uncertainty. The International Journal of Life Cycle Assessment, 19, 429-436.

Hilmarsdottir, G. S., Ogmundarson, Ó., Arason, S., & Gudjónsdóttir, M. (2020). The Effects of Varying Heat Treatments on Lipid Composition during Pelagic Fishmeal Production. *Processes*, *8*(9), 1142.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M. D. M., ... & van Zelm, R. (2017). ReCiPe 2016 v1. 1 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization. *National Institute for Public Health and the Environment: Bilthoven, The Netherlands*.

Iribarren, D., Moreira, M. T., & Feijoo, G. (2010). Implementing by-product management into the life cycle assessment of the mussel sector. *Resources, Conservation and Recycling*, *54*(12), 1219-1230.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

ISO – International Organisation for Standardisation (2006). ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework. https://www.iso.org/standard/37456.html

Jackowski, M., Niedźwiecki, Ł., Jagiełło, K., Uchańska, O., & Trusek, A. (2020). Brewer's Spent Grains—Valuable Beer Industry By-Product. *Biomolecules*, *10*(12), 1669.

Jackson, A. J. & Newton, R. W. (2016). Project to model the use of fisheries by-products in the production of marine ingredients with special reference to omega-3 fatty acids EPA and DHA., 12 pp.

Johansen, J., Bruckner C., Baarset, H., Soula M., & Conceição L. (2019). Innovative methodologies for reusing aquaculture side streams. Deliverable 2.1. GAIN –Green Aquaculture Intensification in Europe. EU Horizon 2020 project grant nº. 77330. 18 pp.

Kok, B., Malcorps, W., Tlusty, M. F., Eltholth, M. M., Auchterlonie, N. A., Little, D. C., Harmsen, R., Newton, R. W. & Davies, S. J. (2020). Fish as feed: Using economic allocation to quantify the Fish In: Fish Out ratio of major fed aquaculture species. *Aquaculture, 528*.

Lurdes, M., Dapkevičius, E., Batista, I., Nout, R., Rombouts, F. M. & Houben, J. H. (1998). Lipid and protein changes during the ensilage of blue whiting. *Food Chemistry, 63*, 97-102.

Maiolo, S., Cristiano, S., Gonella, F., & Pastres, R. (2021). Ecological sustainability of aquafeed: an emergy assessment of novel or underexploited ingredients. *Journal of Cleaner Production*, 294, 126266 (https://doi.org/10.1016/j.jclepro.2021.126266)

Maiolo, S., Forchino, A. A., Faccenda, F., & Pastres, R. (2021). From feed to fork–Life Cycle Assessment on an Italian rainbow trout (Oncorhynchus mykiss) supply chain. *Journal of Cleaner Production*, *289*, 125155.

Martin, M., & Parsapour, A. (2012). Upcycling wastes with biogas production: An exergy and economic analysis. In *Venice 2012: International Symposium on Energy from Biomass and Waste*.

Merino, G., Barange, M., Mullon, C., & Rodwell, L. (2010). Impacts of global environmental change and aquaculture expansion on marine ecosystems. *Global Environmental Change*, *20*(4), 586-596.

Muralikrishna & Manickam (2017). Chapter Five – Life Cycle Assessment. In: *Environmental Management: Science and Engineering for Industry*, BS Publications, India, pp. 57-75.

Newton, R., Malcorps, W., Maiolo, S., Cristiano, S., Moore, H., Micallef, J., Panicz, R., Eljasik, P., Pastres, R., & Little, D. (2021). EISI sustainability approach, and results and analysis. Deliverable 4.3. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 77330.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Parker, R. W. & Tyedmers, P. H. (2012). Life cycle environmental impacts of three products derived from wild-caught Antarctic krill (*Euphausia superba*). *Environ Sci Technol, 46*, 4958-65.

Pauly, D. & Christensen, V. (1995). Primary production required to sustain global fisheries. *Nature, 374*, 255-257.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. & Torres, F. (1998). Fishing Down Marine Food Webs. *Science, 279*, 860-863.

Pravinkumar, M., Eugien, L. X., Viswanathan, C., & Raff, S. M. (2015). Extraction of fish body oil from Sardinella longiceps by employing direct steaming method and its quantitative and qualitative assessment. *Journal of Coastal Life Medicine*, *3*(12), 962-966.

Ramos, S., Vázquez-Rowe, I., Artetxe, I., Moreira, M. T., Feijoo, G. & Zufía, J. (2011). Environmental assessment of the Atlantic mackerel (Scomber scombrus) season in the Basque Country. Increasing the timeline delimitation in fishery LCA studies. *The International Journal of Life Cycle Assessment, 16*, 599-610.

Regueiro, L., Mendez, D., Bruckner, C., Soula, M., & Ferreira, M. (2021). Deliverable 2.8. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 77330. 21 pp.

Rigamonti, L., Grosso, M., & Sunseri, M. C. (2009). Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. *The International Journal of Life Cycle Assessment*, *14*(5), 411-419.

Rosenthal, L. M., Egvad, R., Cristiano, S., Pastres, R., & Hamann, K. (2020). Report on impact assessment indicators monitoring framework. Deliverable D6.1. New technologies, Tools and Strategies for a Sustainable, Resilient and Innovative European Aquaculture. EU Horizon 2020 project grant nº. 862658. 38 pp.

Royer, E., Faccenda, F., & Pastres, R. (2021). Estimating oxygen consumption of rainbow trout (*Oncorhynchus mykiss*) in a raceway: A Precision Fish Farming approach. *Aquacultural Engineering, 92*, 102141.

Schau, E. M., Ellingsen, H., Endal, A. & Aanondsen, S. A. (2009). Energy consumption in the Norwegian fisheries. Journal of Cleaner Production, 17, 325-334.

Service, M.; Grant, J., Icely, J.D., Lopez, M., Moore, H., Micallef, G., Panicz, R., Pastres, R., Rey Planellas, S., & Zhu, C. (2019). Report on Instrumentation of GAIN pilot sites. Deliverable 1.1. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 773330. 63 pp.

SINTEF (2020). Greenhouse gas emissions of Norwegian seafood products in 2017. 114 pp. SINTEF Ocean AS, Trondheim.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

Soula, M., Regueiro, L., Mendez, D., Ferreira, M., & Johansen, J. (2019). Report on Innovative processes for valorising shellfish by - products. Deliverable 2.4. GAIN - Green Aquaculture INtensification in Europe. EU Horizon 2020 project grant nº. 773330. 23 pp.

Stevens, J. R., Newton, R. W., Tlusty, M. & Little, D. C. (2018). The rise of aquaculture by-products: Increasing food production, value, and sustainability through strategic utilisation. *Marine Policy, 90*, 115-124.

Svanes, E., Vold, M. & Hanssen, O. J. (2011). Environmental assessment of cod (*Gadus morhua*) from autoline fisheries. *The International Journal of Life Cycle Assessment, 16*, 611-624.

Tacon, A. G., Hasan, M. R., Subasinghe, R. P., & FAO. (2006). *Use of fishery resources as feed inputs to aquaculture development: trends and policy implications* (No. 1018). Rome: Food and Agriculture Organization of the United Nations.

Thrane, M. (2004). Environmental Impacts from Danish Fish Product. PhD thesis, Department of Development and Planning, Aalborg University.

Tossavainen, M., Lahti, K., Edelmann, M., Eskola, R., Lampi, A. M., Piironen, V., ... & Romantschuk, M. (2019). Integrated utilization of microalgae cultured in aquaculture wastewater: wastewater treatment and production of valuable fatty acids and tocopherols. *Journal of Applied Phycology*, 31(3), 1753-1763.

Tyedmers, P. (2004). Fisheries and Energy Use. *Encyclopedia of Energy,* 2, 683-693.

Vázquez-Rowe, I., Moreira, M. T. & Feijoo, G. (2011). Life Cycle Assessment of fresh hake fillets captured by the Galician fleet in the Northern Stock. *Fisheries Research, 110*, 128-135.

Vazquez-Rowe, I., Villanueva-Rey, P., Mallo, J., De la Cerda, J. J., Moreira, M. T. & Feijoo, G. (2013). Carbon footprint of a multi-ingredient seafood product from a business-to-business perspective. *Journal of Cleaner Production, 44*, 200-210.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), pp. 1218–1230.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

List of tables

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

List of figures

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 773330