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# Life Cycle Assessment of Aquaculture Feed and Application to the Turbot Sector

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**ABSTRACT:** The Spanish turbot aquaculture sector holds a top position in the international market. This activity is mainly developed along the Galician coast (NW Spain). This article evaluates the environmental performance of Galician turbot aquaculture according to the Life Cycle Assessment (LCA) methodology. Previously, on account of the expected relevance of feed for aquaculture, marine aquafeed production was assessed from an LCA perspective. Environmental characterization results for marine feed production led to identify aquafeed formulation as the focus for improvement actions. Furthermore, the environmental profile of feed for continental aquaculture was estimated and compared to that of marine aquafeed. The LCA of marine aquafeed was then implemented into the case study of Galician turbot aquaculture. Electricity use in hatching facilities arose as the main hot spot, ahead of aquafeed and diesel use in ongrowing plants.LCA proved to be a useful tool to provide chain transparency and accountability throughout these case studies.

**Key words:** LCA, Environment, Marine, Aquaculture, Electricity

## INTRODUCTION

Overexploitation of sea resources has brought about a rapid growth in aquaculture due to its potential to reverse the trend towards depletion. However, the environmental performance of aquaculture does not lack a certain degree of controversy. In this respect, comprehensive analysesmust be undertaken in order to assess the suitability of aquaculture from an environmental perspective.

As a complementary tool to local studies on water quality and biological cycles (*e.g.*Praveena*et al.*, 2008; Taseli, 2009; Bhatnagar and Singh, 2010), Life Cycle Assessment (LCA) has often been used to evaluate the environmental performance of both fishing (*e.g.*Hospido and Tyedmers, 2005; Ziegler and Valentinsson, 2008; Vázquez-Rowe *et al.*, 2010) and aquaculture (*e.g.*Aubin *et al.*, 2009; Ayer and Tyedmers, 2009; Iribarren *et al.*, 2010 a) from a life-cycle operational perspective. LCA is a methodologyaimed at assessing the environmental aspects and potential impacts associated with a product by (i) compiling an inventory of relevant inputs and outputs of the product system, (ii) evaluating the potential environmental impacts associated with those inputs and outputs, and (iii) interpreting the results of the inventory analysis and the impact assessment phases in relation to the objectives of the study (ISO, 2006a, b). Due to the holistic nature of LCA, this tool is considered highly appropriate for providing production chain transparency and accountability (Iles, 2007; Ayer *et al.*, 2009).

To date, LCA studies on aquaculture have dealt with different species involving intensive and extensive aquaculture. On the one hand, the assessment of extensive aquaculture has been mainly focused on mussel culture (Lozano *et al.*, 2009, 2010; Iribarren *et al.*, 2010 a, 2011 a). On the other hand, LCA studies on intensive aquaculture have covered a wider range of species such as salmon, trout and shrimp. Despite the diversity of LCAs addressing the environmental characterization of intensive aquaculture practices, a common conclusion can be drawn: the leading role played by feed(Aubin*et al.*, 2009; Ayer and Tyedmers, 2009).

This article deals with the LCA of feed production for intensive aquaculture. Furthermore, marine aquafeed production is implemented as a background process into the LCA of turbot (*Scophthalmus maximus*) aquaculture in Spain in order to thoroughly evaluate the environmental performance of this culture system.

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Spanish turbot aquaculture activities are mainly developed in Galicia (NW coast). In 2007, Galician turbot aquaculture provided more than 5,500 tonnes of this finfish, accounting for an economic turnover close to 50 million euros (Xunta de Galicia, 2008). Thus, turbot farming in Galicia involves around 20% of the Spanish production of finfish from marine aquaculture. Worldwide, Galicia is a reference region regarding turbot aquaculture, with more than half of the total production and turnover in 2006 (FAO, 2009).

Although the Spanish turbot sector holds a top position in the international turbot market, its environmental performance had not yet been evaluated from an LCA perspective. This article aims to fulfil the need for a thorough environmental analysis of this reference sector.

## MATERIALS & METHODS

The goal of this LCA study comprisedthreespecific objectives: (i) environmental characterization of marine aquafeed production in Spain; (ii) assessment of the environmental performance of the Spanish turbot sector (farming and consumption); and (iii) comparison of the environmental profiles of marine and continental aquafeed. Aquafeed production was assessed from raw material production to product transportation. As shown in Fig. 1, seven subsystems were defined to perform the analysis. First, all raw materials required for the industrial production of marine aquafeed were produced in specific factories (SS1) and transported by lorry to the aquafeed plant (SS2). Thereafter, the reception, grinding and mixing of the aquafeed ingredients took place (SS3). The resulting mixture was conditioned and extruded (SS4). Subsequently, drying, greasing and cooling were required. These activities constituted subsystem SS5, where the final product was obtained. This product was then packaged and stored (SS6). Finally, aquafeed was transported by lorry to its final destinations (SS7).

Two systems were distinguished for the LCA of the Galician turbot sector (Fig. 2): turbot farming (S1) and consumption (S2). Turbot farming is usually carried out in three different plants: hatching and nursing facility (from egg to young turbot), growing plant (from young to juvenile turbot) and ongrowing plant (from juvenile to adult turbot). Each of these facilities was defined as a separate subsystem. The final product from SS1.3 was the turbot dispatched to retailers.The second system (*i.e.*, household consumption of farmed turbot) took into account cooking (consumption of electricity, salt and oil), shopping travel, use of paper and plastic wrappers by retailers, use of plastic shopping bags and waste treatment.

The functional unit (FU) is defined by ISO standards as a quantified performance of a product system to be used as the reference unit in an LCA study (ISO, 2006a, b). The FU for the LCA of marine feed production was 1 tonne of marine aquafeed. Similarly, for the estimation of the environmental profile of continental feed, the FU was 1 tonne of continental aquafeed. Finally, the FU for the LCA of the Galician turbot aquaculture sector was 1 kg of turbot consumed at households.

Data for the LCA of aquafeed production were obtained from one of the most important factories in Spain, with an annual production around 50,000 tonnes of feed. Primary activity data were used to quantify the direct inputs and outputs linked to the aquafeed facility. Table 1 summarizes the main inventory data concerning marine aquafeed production. As observed, ingredients and energy carriers were the main inputs to the system.

Background processes are those processes indirectly embedded in the case study. In this study, background processes used the ecoinvent database (Frischknecht *et al.*, 2007) as the source of data for transportation (Spielmann *et al.*, 2007), production of chemicals (Althaus *et al.*, 2007), production of energy carriers (Dones *et al.*, 2007) and waste treatment (Doka, 2007). The ecoinvent database was also used to supply the data for the production of the raw materials in SS1 (Nemecek and Kägi, 2007). In this case, it should be noted that, although a few materials such as blood meal, haemoglobin and vitamins are not included in the ecoinvent database, data relating to their production were based on compounds actually included in this database and which were assumed to be equivalent for the purposes of this study.

Data for turbot farming (S1) were based on the information in the environmental statements of several Galician plants that belong to worldwide leader companies in the aquaculture sector (Isidro de la Cal, 2007; Insuiña-Chapela, 2008; Insuiña-Mougás, 2008; Insuiña-O Grove, 2008; Insuiña-Xove, 2008). The total adult turbot production under assessment was ca. 3,500 tonnes (reference year: 2007). Thus, primary activity data were used for the quantification of the direct inputs and outputs within turbot farms. Table 2summarizes themain inventory data regarding turbot farming (S1). Feed, chemicals (liquid oxygen) and energy carriers were the main inputs to S1.

As far as turbot consumption (S2) was concerned, primary data were used to quantify (i) the consumption of electric energy, oil and salt for cooking, (ii) the use of wrappers by retailers, and (iii) the generation of leftovers as municipal solid wastes.Table 3 presents the main inventory data for the household consumption of turbot (S2).

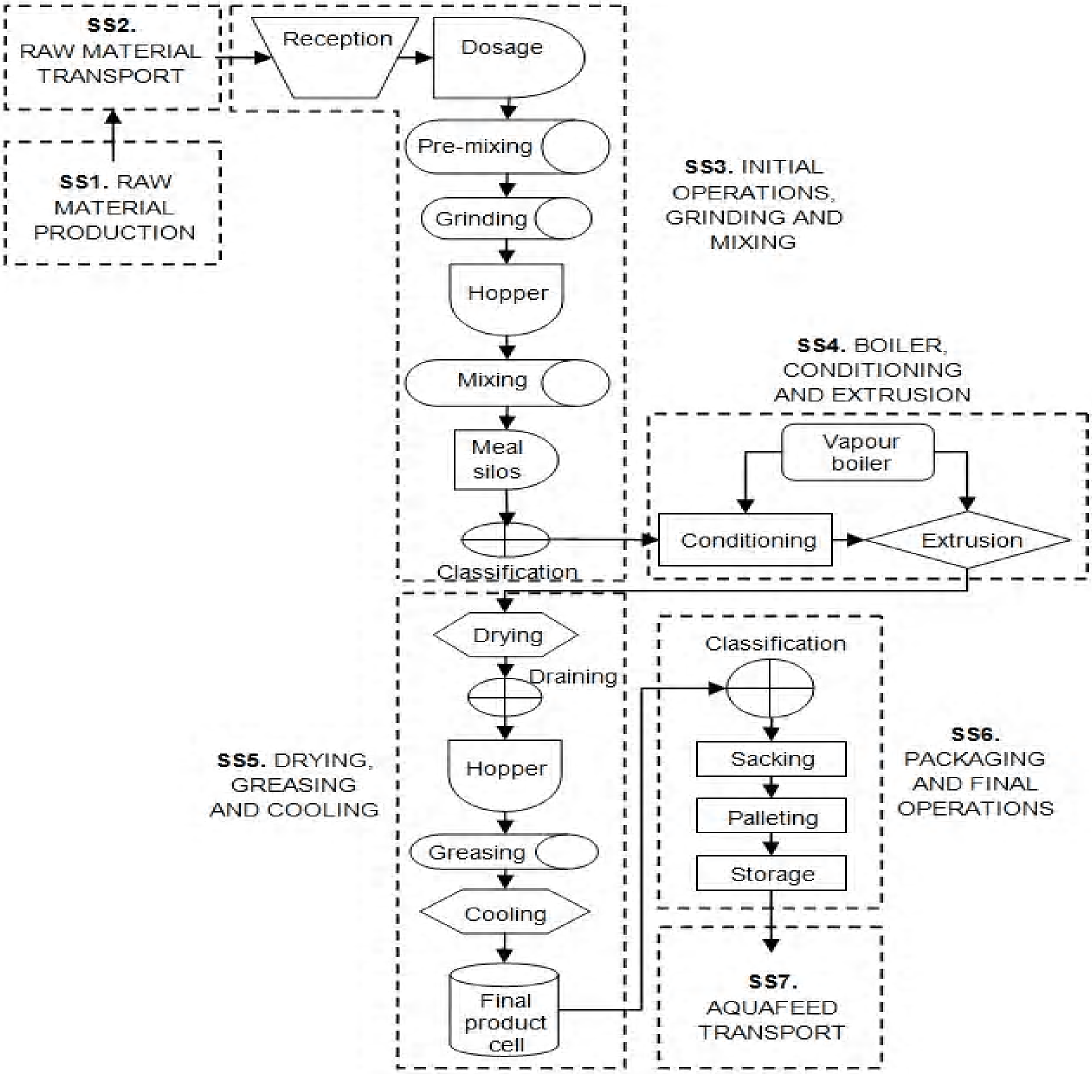


**Fig. 1. Subsystems for the LCA of aquafeed production**

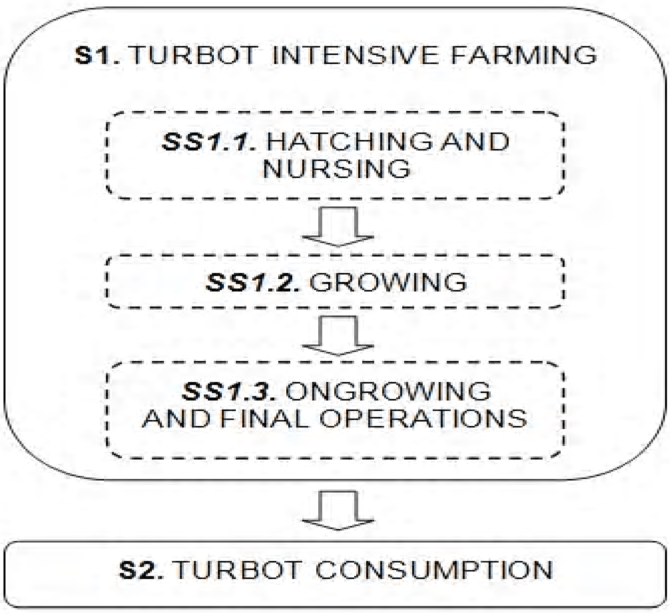


**Fig. 2. Breakdown of the turbot aquaculture sector for LCA**

**Table 1.Summary of inventory data for marine aquafeed production (FU: 1 tonne of marine aquafeed dispatched)**

| INPUTS | | | OUTPUTS | | |
|---|---|---|---|---|---|
| **From the technosphere** | | | **To the technosphere** | | |
| ***Materials*** | ***Value*** | ***Unit*** | ***Product*** | ***Value*** | ***Unit*** |
| Fish meal (SS1) | 192.50 | kg | Dispatched aquafeed product (FU) | 1.00 | t |
| Soybeans (SS1) | 189.95 | kg | ***Wastes to treatment*** | ***Value*** | ***Unit*** |
| Wheat grains (SS1) | 144.50 | kg | Effluent to municipal sewer (SS3) | 0.05 | $m^3$ |
| Recycled fish (SS1) | 80.00 | kg | Solid discharge to combustion (SS3) | 0.32 | kg |
| Fish oil (SS1) | 78.00 | kg | Solid discharge to landfill (SS3) | 0.01 | kg |
| Blood meal (SS1) | 70.00 | kg | Effluent to municipal sewer (SS4) | 0.18 | $m^3$ |
| Haemoglobin (SS1) | 60.00 | kg | Feed discharge to biogas (SS4) | 0.08 | kg |
| Animal fat and oil (SS1) | 50.00 | kg | Solid discharge to combustion (SS4) | 0.64 | kg |
| Pea protein (SS1) | 50.00 | kg | Solid discharge to landfill (SS4) | 0.03 | kg |
| Rape meal (SS1) | 43.00 | kg | Effluent to municipal sewer (SS5) | 0.07 | $m^3$ |
| Soya oil (SS1) | 30.00 | kg | Feed discharge to biogas (SS5) | 0.32 | kg |
| Calcium carbonate (SS1) | 16.00 | kg | Solid discharge to combustion (SS5) | 0.32 | kg |
| Vitamins and minerals (SS1) | 6.05 | kg | Solid discharge to landfill (SS5) | 0.01 | kg |
| Water (SS3) | 0.05 | $m^3$ | Plastic to recycling (SS6) | 0.46 | kg |
| Water (SS4) | 0.58 | $m^3$ | **To the environment** | | |
| Water (SS5) | 0.07 | $m^3$ | ***Emissions to air*** | ***Value*** | ***Unit*** |
| Polyethylene (SS6) | 3.22 | kg | $CO_2$ (SS4) | 101.07 | kg |
| Polypropylene (SS6) | 0.76 | kg | CO (SS4) | 5.93 | g |
| ***Energy*** | ***Value*** | ***Unit*** | $SO_2$ (SS4) | 1.01 | g |
| Electricity (SS3) | 19.13 | kWh | $NO_x$ (SS4) | 26.39 | g $NO_2$ |
| Electricity (SS4) | 89.75 | kWh | | | |
| Natural gas (SS4) | 158.59 | kWh | | | |
| Electricity (SS5) | 57.58 | kWh | | | |
| Natural gas (SS5) | 409.72 | kWh | | | |
| Electricity (SS6) | 11.34 | kWh | | | |
| ***Transport*** | ***Value*** | ***Unit*** | | | |
| Raw material transport (SS2) | 504.08 | t·km | | | |
| Feed transport (SS7) | 530.00 | t·km | | | |

Acronyms of the subsystems: SS1 (raw material production); SS2 (raw material transport); SS3 (initial operations, grinding and mixing); SS4 (boiler, conditioning and extrusion); SS5 (drying, greasing and cooling); SS6 (packaging and final operations); SS7 (product transport).

Regarding the background processes associated with turbot farming and consumption, the ecoinvent database provided data for the production of chemicals (Althaus *et al.*, 2007), packaging materials (Hischier, 2007) and energy carriers (Dones *et al.*, 2007), as well as for transport (Spielmann *et al.*, 2007) and waste treatment (Doka, 2007). Data to quantify the use of plastic bags and shopping travel were adapted from Hospido *et al.* (2006). In this study, both aquafeed production and turbot aquaculture were treated as monofunctional systems and, therefore, no allocation procedure was applied. The quantification of capital goods was avoided on the basis of the long life estimated for the installations (more than 20 years). Electricity production referred to the electricity production mix for Spain as presented in the ecoinvent database (Dones *et al.*, 2007). It should also be noted that, although waste treatment was included within the system boundaries, recycling stayed out due to ecoinvent cut-off criteria (Doka, 2007). SimaPro 7 was

**Table 2.Summary of inventory data for turbot aquaculture (FU: 1 kg of turbot consumed)**

| INPUTS | | | OUTPUTS | | |
|---|---|---|---|---|---|
| **From the technosphere** | | | **To the technosphere** | | |
| ***Materials*** | ***Value*** | ***Unit*** | ***Product*** | ***Value*** | ***Unit*** |
| Liquid oxygen (SS1.1) | 2.905 | kg | Dispatched adult turbot | 1.000 | kg |
| Feed (SS1.1) | 0.542 | kg | ***Wastes to treatment*** | ***Value*** | ***Unit*** |
| Fresh water (SS1.1) | 0.388 | l | Paper and cardboard (SS1.1) | 0.144 | g |
| Diesel (SS1.1) | 0.014 | l | Wood (SS1.1) | 0.505 | g |
| Liquid oxygen (SS1.2) | 0.299 | kg | Plastic (SS1.1) | 0.173 | g |
| Feed (SS1.2) | 0.118 | kg | Polypropylene filters (SS1.1) | 0.135 | g |
| Fresh water (SS1.2) | 1.897 | l | Other non-hazardous wastes (SS1.1) | 2.181 | g |
| Diesel (SS1.2) | 0.068 | l | Hazardous wastes (SS1.1) | 0.476 | g |
| Liquid oxygen (SS1.3) | 0.274 | kg | Paper and cardboard (SS1.2) | 0.250 | g |
| Feed (SS1.3) | 0.891 | kg | Wood (SS1.2) | 3.513 | g |
| Fresh water (SS1.3) | 18.115 | l | Scrap (SS1.2) | 2.345 | g |
| Diesel (SS1.3) | 0.934 | l | Plastic (SS1.2) | 1.153 | g |
| ***Energy*** | ***Value*** | ***Unit*** | Other non-hazardous wastes (SS1.2) | 7.022 | g |
| Electricity (SS1.1) | 14.843 | kWh | Hazardous wastes (SS1.2) | 1.191 | g |
| Electricity (SS1.2) | 3.152 | kWh | Scrap (SS1.3) | 1.370 | g |
| Electricity (SS1.3) | 2.045 | kWh | Paper and cardboard (SS1.3) | 1.330 | g |
| ***Transport*** | ***Value*** | ***Unit*** | Plastic and wood (SS1.3) | 42.867 | g |
| Product transport to retailers (SS1.3) | 0.425 | t·km | Other non-hazardous wastes (SS1.3) | 36.860 | g |
| **From the environment** | | | Hazardous wastes (SS1.3) | 1.310 | g |
| ***Materials*** | ***Value*** | ***Unit*** | **To the environment** | | |
| Seawater (SS1.1) | 0.360 | l | ***Emissions to air*** | ***Value*** | ***Unit*** |
| Seawater (SS1.2) | 1.759 | l | $SO_2$ (SS1.1) | 0.075 | g |
| Seawater (SS1.3) | 15.041 | l | CO (SS1.1) | 0.015 | g |
| **OUTPUTS** | | | $CO_2$ (SS1.1) | 0.114 | kg |
| **To the environment** | | | $NO_x$ (SS1.1) | 0.101 | g $NO_2$ |
| ***Emissions to the ocean*** | ***Value*** | ***Unit*** | $SO_2$ (SS1.2) | 0.367 | g |
| Suspended solids (SS1.1) | 1.260 | mg | CO (SS1.2) | 0.072 | g |
| Nitrite (SS1.1) | 0.047 | mg | $CO_2$ (SS1.2) | 0.557 | kg |
| Phosphate (SS1.1) | 0.036 | mg | $NO_x$ (SS1.2) | 0.495 | g $NO_2$ |
| Total organic carbon (SS1.1) | 0.468 | mg | $SO_2$ (SS1.3) | 3.507 | g |
| Suspended solids (SS1.2) | 6.685 | mg | CO (SS1.3) | 0.683 | g |
| Nitrite (SS1.2) | 0.070 | mg | $CO_2$ (SS1.3) | 5.315 | kg |
| Phosphate (SS1.2) | 0.176 | mg | $NO_x$ (SS1.3) | 4.729 | g $NO_2$ |
| Total organic carbon (SS1.2) | 2.815 | mg | | | |
| Suspended solids (SS1.3) | 45.395 | mg | | | |
| Nitrite (SS1.3) | 1.526 | mg | | | |
| Phosphate (SS1.3) | 3.688 | mg | | | |
| Total organic carbon (SS1.3) | 24.905 | mg | | | |
| Acronyms of the subsystems: SS1.1 (hatching and nursing); SS1.2 (growing); SS1.3 (ongrowing and final operations). | | | | | |

**Table 3. Summary of inventory data for turbot consumption (FU: 1 kg of turbot consumed)**

| INPUTS FROM THE TECHNOSPHERE | | |
|---|---|---|
| ***Materials*** | ***Value*** | ***Unit*** |
| Dispatched adult turbot | 1.00 | kg |
| Paper film | 19.88 | g |
| Plastic film (LDPE) | 3.01 | g |
| Oil | 53.86 | g |
| Salt | 7.96 | g |
| Plastic bags (LDPE) | 3.80 | g |
| ***Transport*** | ***Value*** | ***Unit*** |
| Shopping travel | 0.14 | m |
| ***Energy*** | ***Value*** | ***Unit*** |
| Electricity | 0.16 | kWh |
| **OUTPUTS TO THE TECHNOSPHERE** | | |
| ***Wastes to treatment*** | ***Value*** | ***Unit*** |
| Municipal solid waste: plastic bags | 3.80 | g |
| Municipal solid waste: leftovers and others | 332.60 | g |

the software used for the computational implementation of the life cycle inventories (Goedkoop *et al.*, 2008). Classification and characterization following ISO guidelines (ISO, 2006a, b) were performed in order to assess the potential environmental impacts of marine aquafeed production and turbot aquaculture.In particular, CML 2001 was the method used for the environmental characterization (Heijungs *et al.*, 1992;Guinée *et al.*, 2001). Six impact potentials were considered: abiotic depletion (AD), global warming(GW), ozone layer depletion (OD), photochemical oxidant formation (POF), acidification (Ac) andeutrophication (Eu).

## RESULTS & DISCUSSION

The environmental characterization of marine aquafeed production led to identify those subsystems with the highest contributions to theselected impact categories. Fig. 3 shows the percentage contribution of the seven aquafeed subsystems to the potential environmental impacts.As observed, raw material production (SS1) involved contribution percentages ranging from 18% (GW) to 93% (POF), and dominated all impact categories apart from GW. The latter was dominated by SS4 (*i.e.*, boiler operation, conditioning and extrusion), with a percentage of 36%. The remaining subsystems showed contributions below

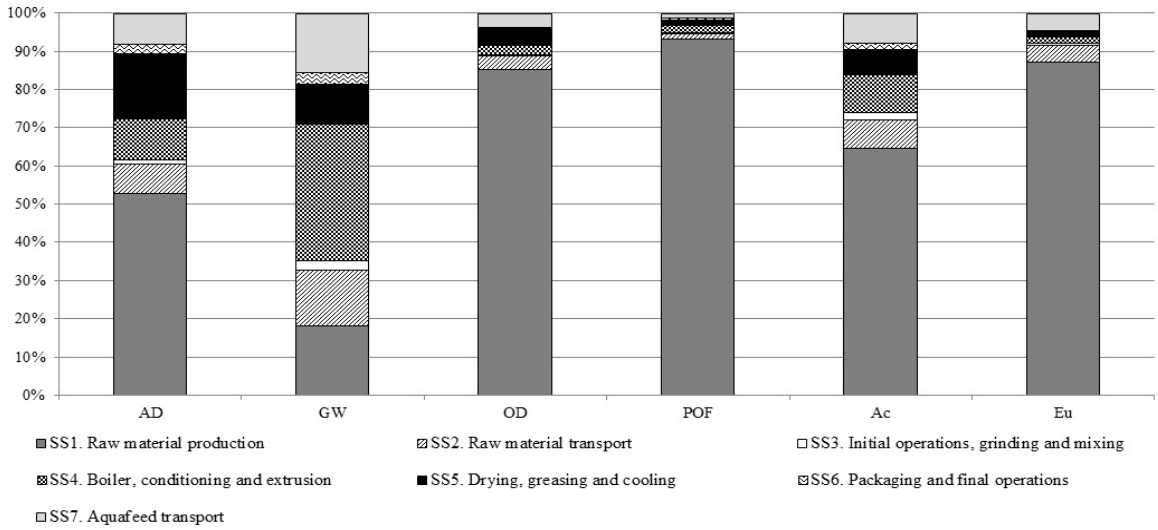


**Fig. 3. Subsystem contribution to the environmental impact potentials for marine aquafeed production (AD: abiotic depletion; GW: global warming; OD: ozone layer depletion; POF: photochemical oxidant formation; Ac: acidification; Eu: eutrophication)**

17% for the different impact categories. In particular, SS3 (initial operations, grinding and mixing) and SS6 (packaging and final operations) showed very low percentages, ranging from 0% to 3%.

Furthermore, the processes behind these contributions were identified. Given the highnumber of processes involved in marine aquafeed production, Table 4 shows a summary of the most relevant processes. All sections with a contribution above 5% were gathered in this table. Within this reduced set, the role played by the processes relating to raw material production stood out for all impact categories. Their contribution to Ac was closely linked to the emission of $NO_x$ and $SO_2$ to air, while their contribution to Eu was mainly due to nitrate emissions to water. Moreover, the emission of CO and Halon 1301 to air determined their contribution to POF and OD, respectively. In addition to the leading role of raw material production, significant contributions to GW were found due to transportation (SS2 and SS7), electricity use (SS4 and SS5) and direct emissions to air (SS4). $CO_2$ was the main substance behind the potential GW impact. Natural gas use in SS5 and, to a lesser extent, in SS4 significantly contributed to AD.

The LCA of marine aquafeed production resulted in the identification of the environmental hot spots of this system. These hot spots were mainly related to raw material production. In particular, soybeans, fish meal and wheat grains were the most contributing raw materials. This fact was closely linked to the demand of great amounts of these specific materials according to the current aquafeed formulation. Furthermore, ifspecial attention is paid to global warming, then additional hot spots include transport and direct emissions to air from boilers. Therefore, improvement actions in the field of marine aquafeed production should focus on:

- Environmental analysis of new ingredient ratios. Different combinations of the ingredients are possible. However, suitable contents of proteins, lipids and phosphorus have to be guaranteed. The selection of new ingredient ratios will depend on what impact categories are preferred in terms of environmental mitigation. For instance, formulations that use more soya beans and wheat grains but less fish meal are expected to entail a better environmental performance regarding AD, GW and OD.

- Environmental assessment of new raw materials. In addition to changes in ingredient ratios, research on novel protein sources for aquafeed should continue. In this respect, novel raw materials should be assessed from an environmental perspective in order to discuss the potential environmental consequences of replacement. For example, novel fish meals leading to a better environmental profile for this key raw material would entail relevant improvements in the environmental performance of aquafeed production.

**Table 4. Process contribution (%) in marine aquafeed production**

| | AD | GW | OD | POF | Ac | Eu |
|---|---|---|---|---|---|---|
| Fish meal (SS1) | 25.12 | 31.05 | 69.61 | -1.07 | 13.98 | -77.39 |
| Soybeans (SS1) | 2.43 | 9.43 | 0.89 | 88.13 | 17.82 | 69.22 |
| Wheat grains (SS1) | 6.86 | -18.79 | 2.41 | 1.59 | 12.65 | 29.15 |
| Fish oil (SS1) | 3.01 | 6.12 | 7.62 | 0.46 | 3.47 | 2.07 |
| Blood meal (SS1) | 2.43 | 4.77 | 0.76 | 0.85 | 5.03 | 1.35 |
| Pea protein (SS1) | 2.34 | -0.11 | 0.99 | 0.46 | 3.55 | 53.62 |
| Rape meal (SS1) | 1.48 | -20.10 | 0.50 | 1.32 | 3.22 | 6.77 |
| Soya oil (SS1) | 2.85 | 4.33 | 1.06 | 1.93 | 7.18 | 25.97 |
| Raw material transport (SS2) | 7.65 | 14.73 | 3.58 | 1.25 | 7.41 | 4.41 |
| Atmospheric emissions (SS4) | 0.00 | 23.57 | 0.00 | 0.02 | 0.31 | 0.20 |
| Natural gas (SS4) | 5.21 | 1.35 | 1.54 | 0.13 | 0.18 | 0.11 |
| Electricity (SS4) | 5.50 | 10.58 | 0.87 | 1.77 | 9.36 | 1.31 |
| Natural gas (SS5) | 13.45 | 3.49 | 3.97 | 0.34 | 0.47 | 0.27 |
| Electricity (SS5) | 3.53 | 6.79 | 0.56 | 1.13 | 6.00 | 0.84 |
| Product transport (SS7) | 8.05 | 15.49 | 3.76 | 1.31 | 7.79 | 4.63 |
| TOTAL (%) | 89.90 | 92.69 | 98.12 | 99.61 | 98.44 | 122.53 |

Acronyms: AD(abiotic depletion); GW(global warming); OD(ozone layer depletion); POF(photochemical oxidant formation); Ac(acidification); Eu(eutrophication); SS1(raw material production); SS2(raw material transport); SS4(boiler, conditioning and extrusion); SS5(drying, greasing and cooling); SS7(product transport).

- Revision of the logistical planning regarding product and raw material transportation. This measure is directed towards the minimization of the number of trips and travel distances required to satisfy the transport needs of raw materials and products in aquafeed factories so that economic and environmental improvements are achieved. GW, AD and Ac are the impact categories that would benefit most from this measure.

- Minimization of the natural gas demand. This reduction would involve improvements in GW due to lower levels of emissions to air, as well as in AD because of the decrease in the natural gas amount.

In order to establish a simple comparison between marine and continental aquafeed, the only difference between both types of feed was assumed to be the raw materials produced in SS1. The rest of subsystems involved in aquafeed production were considered to present the same inventory datafor marine and continental aquafeed. Formulation data from the feed company under study were used (Iribarren, 2010). The different formulations gave rise to different environmental characterization results for the two aquafeed production systems. Table 5 compares the characterization results computed for raw material production (SS1) in both cases. Relevant changes were observed. For instance, GW for continental feed doubled the value for marine feed. On the contrary, Eu was much lower for continental aquafeed. These variations in SS1 resulted in notable changes in the final characterization values when assessing the whole aquafeed production systems, as also shown in Table 5.

The LCA of marine aquafeed was implemented as a reliable background process into a wider case study: turbot aquaculture. This case study covered turbot farming and consumption. The total environmental characterization results per kg of consumed turbot were: 117.30 g Sb eq (AD), 19.49 kg $CO_2$ eq (GW), 1.52 mg CFC-11 eq (OD), 5.86 g $C_2H_4$ eq (POF), 127.42 g $SO_2$ eq (Ac) and 11.94 g $PO_4^{3-}$ eq (Eu).

The environmental characterization of Galician turbot aquaculture led to identify the subsystems and processes with the highest contributions to the selected impact categories. Fig. 4 allows the identification of the subsystems that arose as the main sources of potential environmental impact. Turbot consumption(S2)proved to be a low contributing subsystem, except for Eu (percentage contribution of 21%). On the contrary, hatching and nursing (SS1.1) dominated all impact categories apart from OD, which was dominated by ongrowing and final operations (SS1.3). The contribution percentages ranged from 41% (OD) to 63% (Ac) for hatching and nursing (SS1.1), and from 21% (Ac) to 46% (OD)for ongrowing and final operations (SS1.3). The contribution of growing (SS1.2) was deemed relevant, but accounting for significantly lower percentages than SS1.1 and SS1.3. Thus, the greatest contribution of growing was observed for Ac, with a percentage of 14%.

In order to identify the processes that accounted for the most relevant contributions to the potential environmental impacts, Table 6shows the sections with a contribution above 5% in any category. The high electricity demand of hatching and nursing (SS1.1) was found to be the main reason for the high contribution of SS1 to all impact categories. In this respect, $SO_2$ emissions to air related to electricity production were behind the high contribution to Ac and POF, while $CO_2$

**Table 5. Comparison of the characterization results for marine and continental aquafeed**

| Impact category | Unit | SS1 marine | SS1 continental | Total marine | Total continental | Ratio SS1 continental/marine | Ratio Total continental/marine |
|---|---|---|---|---|---|---|---|
| AD | kg Sb eq | 3.20 | 4.11 | 6.06 | 6.98 | 1.29 | 1.15 |
| GW | kg $CO_2$ eq | 77.84 | 181.26 | 428.84 | 532.27 | 2.33 | 1.24 |
| OD | g CFC-11 eq | 0.24 | 0.35 | 0.29 | 0.39 | 1.44 | 1.37 |
| POF | kg $C_2H_4$ eq | 0.84 | 0.71 | 0.90 | 0.77 | 0.85 | 0.86 |
| Ac | kg $SO_2$ eq | 3.02 | 3.59 | 4.67 | 5.24 | 1.19 | 1.12 |
| Eu | kg $PO_4^{3-}$ eq | 1.47 | 0.27 | 1.68 | 0.48 | 0.18 | 0.29 |

Acronyms: AD(abiotic depletion); GW(global warming); OD(ozone layer depletion); POF(photochemical oxidant formation); Ac(acidification); Eu(eutrophication); SS1(raw material production).

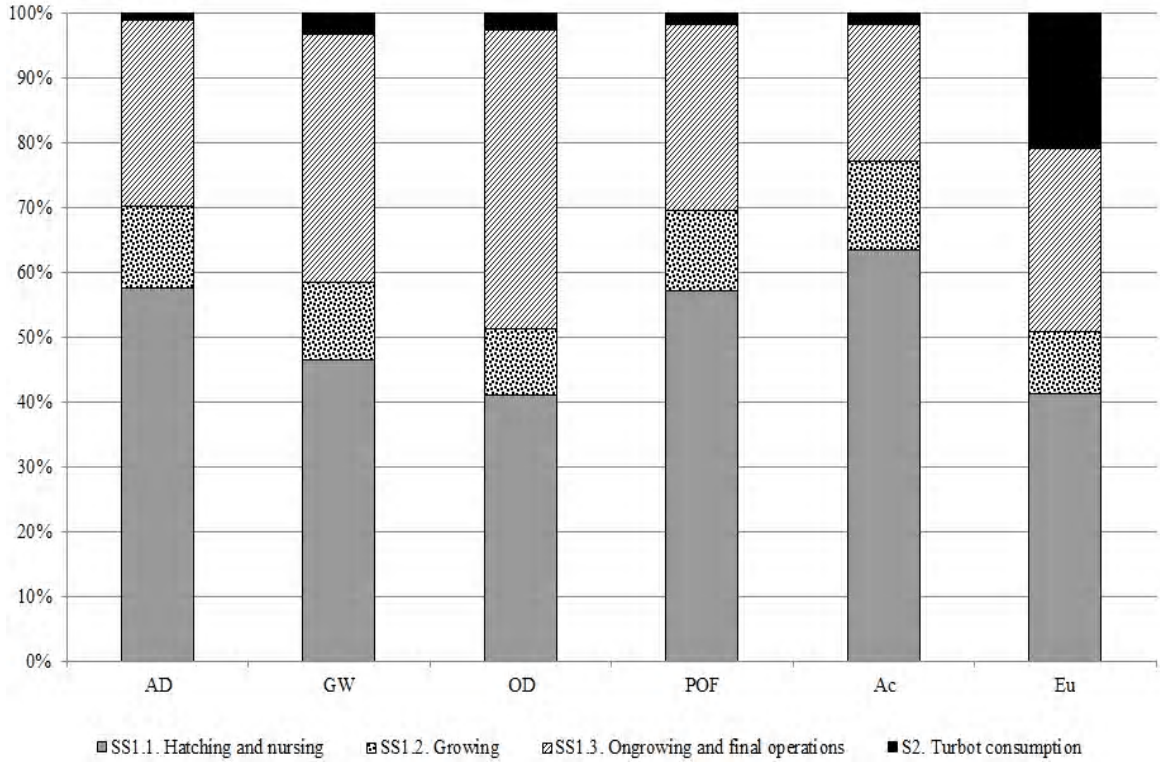


**Fig. 4. Contribution to the environmental impact potentials in turbot aquaculture and consumption (AD: abiotic depletion; GW: global warming; OD: ozone layer depletion; POF: photochemical oxidant formation; Ac: acidification; Eu: eutrophication)**

**Table 6. Process contribution (%) in turbot farming and consumption**

| | AD | GW | OD | POF | Ac | Eu |
|---|---|---|---|---|---|---|
| Liquid oxygen (SS1.1) | 7.46 | 6.07 | 3.44 | 3.77 | 4.45 | 2.50 |
| Aquafeed (SS1.1) | 2.80 | 1.19 | 10.22 | 8.32 | 1.99 | 7.64 |
| Electricity (SS1.1) | 47.05 | 38.50 | 27.02 | 44.86 | 56.68 | 30.56 |
| Electricity (SS1.2) | 9.99 | 8.18 | 5.74 | 9.53 | 12.04 | 6.49 |
| Emissions (SS1.3) | 0.00 | 27.27 | 0.00 | 3.19 | 5.16 | 5.18 |
| Aquafeed (SS1.3) | 4.61 | 1.96 | 16.80 | 13.67 | 3.26 | 12.57 |
| Diesel (SS1.3) | 15.98 | 2.04 | 23.89 | 4.64 | 3.76 | 3.93 |
| Electricity (SS1.3) | 6.48 | 5.30 | 3.72 | 6.18 | 7.81 | 4.21 |
| Oil (S2) | 0.40 | 0.94 | 2.20 | 1.19 | 1.07 | 18.71 |
| TOTAL (%) | 94.76 | 91.46 | 93.03 | 95.34 | 96.22 | 91.79 |

Acronyms: AD(abiotic depletion); GW(global warming); OD(ozone layer depletion); POF(photochemical oxidant formation); Ac(acidification); Eu(eutrophication); SS1.1 (hatching and nursing); SS1.2 (growing); SS1.3 (ongrowing and final operations); S2 (turbot consumption).

and $NO_x$ emissions to air were closely linked to the potential GW and Eu impacts, respectively. The emission of Halon 1211 and Halon 1301 to air was the main cause of OD. The contribution to AD was linked to the coal demand for electricity production according to the Spanish mix (Dones *et al.*, 2007).

Aquafeed requirement also arose asa key environmental issue, especially for hatching and nursing (SS1.1) and ongrowing and final operations (SS1.3), as these subsystems showed higher feed demands than SS1.2. This result justifies having performed a thorough study of feed production. Halon 1301 emissions to air, CO emissions to air and nitrate emissions to water were highly responsible for the contributions of aquafeed to OD, POF and Eu, respectively.

It should also be highlighted that direct emissions to air from SS1.3 (ongrowing and final operations) showed a contribution of 27% to GW, mainly due to direct $CO_2$ emissions. Moreover, diesel demand in SS1.3 gave rise to contributions of 24% to OD and 16% to AD. This contribution to OD was mainly caused by the emission of Halon 1301 to air. Furthermore, Table 6 shows that the relevant contribution of turbot consumption to Euwas linked to the use of oil for cooking at households, since oil production entailed relevant nitrate emissions to water.

The main environmental hot spot of turbot aquaculture was found to be electricity use in hatching and nursing facilities, ahead of aquafeed and diesel for ongrowing. Therefore, improvement actions in turbot aquaculture should pursue the minimization of the electricity demand of hatching. Nevertheless, aquaculture plants should also promote the production of more eco-friendly aquafeed. Secondary measures to enhance the environmental performance of the turbot sector should deal with the diesel demand of ongrowing facilities.

Finally, the environmental profile computed for farmed turbot could be compared to that of other species evaluated in previous LCA studies. For instance, Iribarren *et al.* (2010 b, 2011 b) provided life-cycle GW results for a wide range of fishing species, some of which (*e.g.* hake, cod and pollack) could be functionally replaced with farmed turbot. According to the GW value computed here for cultured turbot and the carbon footprints reported in Iribarren *et al.* (2010 b, 2011 b) for replaceable species, replacement with farmed turbot would be disadvantaged in terms of global warming. This observation also leads to expect a more favourable performance for turbot caught wild than for farmed turbot.

## CONCLUSION

LCA proved to be a useful tool for the evaluation of the environmental performance of aquafeed production and turbot aquaculture. LCA methodology provided chain transparency and accountability throughout these case studies, leading to the identification of the most relevant environmental issues. Moreover, an extended collection of inventory data for these processes was supplied.

From an environmental perspective, aquafeed manufacturers shouldfocus improvement actions on feed formulation. Research on new raw materials and different ingredient ratios should be promoted. Environmental improvements in the field of aquafeed production would benefit not only feed manufacturers but also fish farmers. However, the main recommendation for turbot producers isto minimize the electricity demand of hatching facilities.

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