8. Preliminary LCA of three Peruvian fishmeal plants

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ABSTRACT

Fishmeal and fish oil are largely used as input to several animal feed industries, but there is a lack of LCAs on Peruvian fishmeal plants, despite their predominance in the global supply. Preliminary LCAs where performed on three different types of Peruvian fishmeal plants with the objective of comparing them and suggesting ways of limiting their impacts. Two system boundaries were used: one including the fishery and another excluding it in order to enable others to use our dataset. We used the SimaPro software, the ecoinvent 2.2 database and the ReCiPe method. Despite the predominant impact of the use phase, in particular consumption of fossil energy, the construction and maintenance phases contribute significantly when fishing is excluded from the system boundaries. Furthermore, existing screening LCAs of the use phase underestimate significantly its environmental impacts. The environmental benefit of using natural gas instead of heavy fuel as energy source is quantified. The comparison of environmental impacts between different qualities of fishmeal shows higher impacts of residual fish meal, intermediate impact of standard fishmeal and lower impacts prime fishmeal. Future studies on other fishmeal and residual fishmeal plants should take into account the construction and maintenance phases, and more items in the use phase than in historical screenings. There is room to decrease the environmental impact of this industry in Peru.

Keywords: Animal feed; Cleaner production; Fisheries; Fishmeal; Fish oil; Peruvian anchovy

1. Introduction

1.1. Rationale

Intensive or semi-intensive farming of livestock and aquatic animals requires feed with high protein and lipid contents, some of which must be of animal origin to supply essential amino and fatty acids. Those two ingredients are found in fishmeal and fish oil (FMFO) respectively. Although the substitution of those two commodities by cheaper products of vegetal and animal origin is increasing, the increase in farming of livestock and aquatic animals counterbalances these substitutions and the FMFO demand for animal feed is still growing. There is also a growing demand of fish oil for human consumption (omega-3).

In the aquaculture sector, LCAs demonstrated that feed provision accounts for a large share in many of the environmental impacts in this sector (Henriksson et al., 2012, 2015). FMFO contribution within fish feed environmental impacts is substantial and usually ranks first in fish feed of carnivorous species such as salmon and trout (e.g. Pelletier et al. 2009; Avadí et al., 2015). Moreover, feeds for farmed herbivore fish often include small amounts of FMFO, thus representing a large aggregated consumption due to the large share of these families in the worlds' aquaculture output (Chiu et al., 2013; Henriksson et al., 2014). Nonetheless the precision of FMFO impacts in most studies is hindered by the lack of a life cycle inventory (LCI) of the FMFO production process. As far as we know, only Denmark benefits from a rough LCI of fishmeal plants, whereas Peru and Norway only benefit from an even more superficial screening. The Danish fishmeal plant LCI, available at http://www.lcafood.dk/, was performed in 2000 and most its data were used as proxies for the other LCIs, in addition to few generic data for freshwater use and waste water (FAO, 1986; COWI, 2000). According to Henriksson et al. (2014) fishmeal environmental impacts could differ with two orders of magnitude depending upon its origin.

1.2. The Peruvian FMFO sector

The Peruvian FMFO sector produces in average (2006-2015) 1.183 million t of fishmeal and 230 000 t of fish oil per year, which represent 24% and 23% of the global production, respectively. Peru exports most of this production which relies on the extremely high abundance of the Peruvian anchovy (*Engraulis ringens*), commonly referred to as ‘anchoveta’. This species is also characterized by its high variation in abundance at different time scales (seasonal, inter-annual and inter decadal).

The production of FMFO is supplied by the Peruvian industrial fleet of purse-seiners, which by law consists of vessels whose holding capacities are over 32.6 m^3 and land their catches exclusively for reduction into FMFO. This fleet subdivides into two major segments: steel vessels and wooden hull vessels (Fréon et al., 2014b). There is also a Peruvian wooden small- and medium-scale (SMS) fleet of purse-seiners with holding capacity under 32.6 m^3. SMS vessels are allowed by legislation to land anchoveta exclusively for direct human consumption (DHC), but from 2012, 10% of the small-scale anchoveta landings and 40% of the medium-scale one can be legally redirected to reduction under certain conditions. Up to 2008 the industrial fishery was regulated by a single quota whereas the SMS fishery benefited from a full open access. From 2009, an Individual Vessel Quotas (IVQs) system was fully implemented for the industrial fleet. Illegal, unreported, and unregulated (IUU) fishing is a recurrent problem in Peru (although improving), and in the SMS fleets operations it reached 200% over the officially reported figures (Fréon et al., 2014b).

Three different categories of fishmeal were produced in Peru during the study period (2010-2013), where quality depends mainly on protein, lipid and salt content:

1) Standard fishmeal, also are referred to as "fair average quality" (FAQ), usually produced using direct hot air during the drying phase (“flame drying” or “direct-fire drying”),
2) Prime fishmeal,
3) Super prime fishmeal; for producing prime fishmeal and super prime fishmeal, special driers are needed; typically hot air is produced by circulation of steam inside the dryer (“indirect steam drying”).

There is no clear definition of fish oil categories in Peru, except for the recent (2009) European sanitary regulation on fish oil importation. There are three main types of fishmeal plants operating in Peru:

1) Residual plants which, in principle, are only allowed to process fish residuals and unsuitable fish of different species aimed at DHC. In practice, most of these plants process 30-50% of IUU anchoveta;
2) Traditional FAQ plants, which use mostly anchoveta as raw material. Both residual and traditional plants are producing only FAQ fishmeal and consume mainly heavy fuel as energy source;
3) Modern steam plants, which produce both and prime and super prime quality fishmeal and also use mostly anchoveta as raw material. These plants consume both heavy fuel and natural gas when available.

All traditional and modern steam plants belong to fishing companies that operate their own steel vessels and, in addition, buy fish from the wooden industrial vessels. In the recent period, the quality of the Peruvian FMFO increased and the production of FAQ fishmeal remains only in small plants.

There is a total of 207 fishmeal plants constructed in Peru, including 37 with cancelled permits, which correspond to an impressive total processing capacity of 11 400 t per hour (9 350 excluding plants with cancelled permits).

These plants are located all along the Peruvian coast, with concentration close to the main fishing harbours, which generates social conflicts between the industry and the local population about the nuisances of the plants (odour nuisance and costal water contamination). One important characteristics of nearly all the large plants is that they benefit from a floating transfer terminal located several hundred m offshore, where the fish is pumped from the holds of fishing vessels and sent directly to the plant by an underwater pipe.

2. Goal and Scope

2.1. LCA Goals

The intended applications of our results are: 1) to provide data and related recommendations for environmental protection in Peru in order to allow a future greening of the FMFO supply chain; and 2) to provide results of life cycle inventory (LCI), LCI analysis and life cycle impact assessment (LCIA) that can be used in LCAs of any supply chains where fishmeal or fish oil are key. The major limitations of this study are: 1) the limited number of sampled plants (one per category); 2) the usual inherent limitations of LCA when applied to fisheries[1]; 3) the lack of characterisation of the impacts of certain substances released to the environment (oils, some antifouling substances, biological oxygen demand (BOD), etc.) including their odour nuisance; and 4) as usual in LCAs, impact categories and associated characterisation factors are often insufficient, subject to uncertainty and subjectivity in the weighting factors, and prone to biases and errors (Vázquez-Rowe et al., 2012; Avadí and Fréon, 2013).

2.2. Scope

The studied system consists in two major processes: 1) capturing fish at sea and delivering it to the terminal of a fishmeal plant, and 2) transforming this raw material into FMFO. Because process 1) is already fully documented (Avadí et al., 2014a,b; Fréon et al., 2014b), this work concentrates in process 2) and its sub-processes. The function of the system is the procurement of the two commodities, fishmeal and fish oil.

In order to reach our two intended applications, two different types of functional units (FUs) were used: an output-based one and a process-based one. The first type of FU is the delivery of one metric tonne (t) of each of the two commodities at the gate of the plant, using gross energy content for the allocation of impacts between those two coproducts, and considering separately three categories of commodities in the case of fishmeal: residual, FAQ and Prime or Super Prime. We do not consider any category of fish oil in the definition of the corresponding FU. These output-based FUs allow reaching our first intended application (greening the Peruvian supply chain of FMFO).

In order to reach our second intended application (providing generic results) process-based FUs were retained. They consist in the processing of 1 t of raw material entering at the floating terminal of the plant and used to produce the same three categories of fishmeal. The fact that our process-based FUs consider the raw material input rather than the outputs takes into account most of the consequences of changes in the conversion ratio according to the raw material, providing that the LCA practitioner that use this kind of FUs knows the actual value of the conversion ratio of his/her case study.

The reference flows are one t of Peruvian fish oil or Peruvian fishmeal of specified quality (out of three) for the output-based FUs. In the case of process-based FUs, the reference flow is one t of raw material as the major input of a plant aimed at producing two co-products (fish oil and fishmeal of a specified quality).

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[1] The major limitations are the need for standardisation of fisheries LCA research (fisheries-specific impact categories, inventory details, normalisation references, etc.) and the weakness of some methodological assumptions, as discussed in Vázquez-Rowe et al. (2012) and Avadí and Fréon (2013).

Because our goals are mostly retrospective, accounting and descriptive ones, the retained LCI modelling framework is an attributional one. Although we address the consequences of a change of the main energy source from heavy fuel to natural gas, consequential LCA was not used because existing Peruvian data allows this comparison. The allocation approach was retained based on energy content as a physical relationship (Ayer et al., 2006).

The system boundary of the study for the output-based FUs is "from cradle to gate" and includes the extraction of the raw material (fishing), its delivery at the plant terminal, its processing and conditioning in the plant. In contrast, the boundary for the process-based FUs is "from gate to gate" (Figure 3). The following three life cycle stages of the fishmeal plants were retained: construction, use and maintenance. The factory infrastructures were considered, as well as the large storage area and the total land occupation, but the end of life (EoL) stage was ignored for the plant (not for the fishing vessels when using the output-based FUs). The main reason for the exclusion of the EoL phase was the lack of previous experience of full dismantlement in Peru. We made the assumption that EoL environmental impact is limited base on: 1) the large duration of life of the equipment (up to 40 years) allowed by an excellent maintenance; 2) the tradition in Peru to reuse equipment; 3) the results of other LCA studies of food production (Hall and Howe, 2012).

Inventory data were collected in the period 2010–2013 and encompass averaged fishery data from all the Peruvian anchoveta fleets and three fishmeal plants. These plants were numbered chronologically as Plant 1 for the traditional FAQ plant, Plant 2 for the modern steam plant producing prime fishmeal and Plant 3 for the residual plant (Table 3). The cut-off rules used for the fishing process are detailed in Fréon et al. (2014b,c). Regarding Plant 3, only a screening LCI was performed on the field. In order to allow LCIA comparisons between the three plants, this initial LCI was expanded by assigning to Plant 3 the rescaled Plant 1 LCI. Although the rescaling factors were very rough, the comparison makes sense mainly because the main LCI item (fuel use) was available.

Table 3: Major characteristics of the three sampled plants

Characteristic	Plant 1: traditional FAQ	Plant 2: Modern steam	Plant 3: Residual
Type of fishmeal produced	100% FAQ	100% Prime	100% FAQ
Type of fuel used for heating	Heavy fuel	98% gas converted in 100% by simulation in the LCA.	Heavy fuel
Number of production lines	2	3 (2 Prime fishmeal, 1 FAQ)	1
Average instantaneous processing yield (t/h)	88	114	5
Average processing yield per working hours* (t/h)	70	100	4
Average annual working hours (h)	700	1400	1900 (estimated)
Fresh fish processed (t)	48 430	155 535	9 600
Base years**	2008, <u>2009</u>, 2010	2007, 2008, <u>2009</u>, 2010	<u>2012</u>

* Taking into account daily maintenance (4 h per working day) and other delays. ** Major one underlined

The LCIA method ReCiPe v1.07 (Goedkoop et al. 2009) was used as available in the LCA software SimaPro v7.3, and LCI database ecoinvent v2.2 was used for background processes. The egalitarian perspective of ReCiPe was retained because it is the most precautionary one (Goedkoop et al. 2009).

The major LCI datasets were provided by the major fishing companies for the fishing sub-system (details in Fréon et al., 2014c) and by a single fishing company (anonymous) regarding Plants 1 and 2. In both cases we had access to reliable data. Fossil energies, electricity mix and materials consumed by the fishing fleet or the plant, and combustion of fuels in industrial boilers were modelled specifically for Peru.

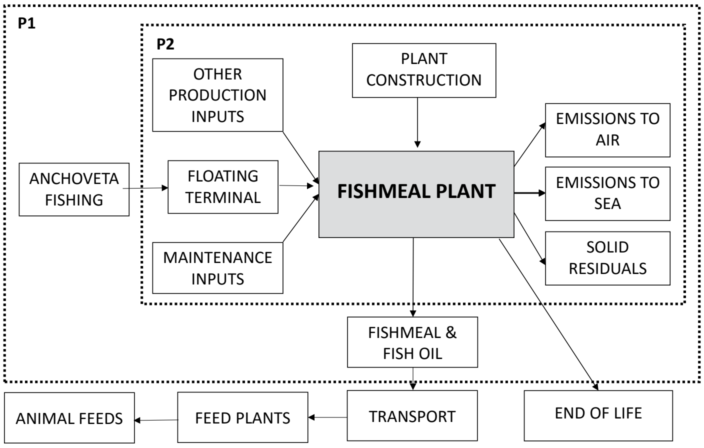


Figure 3: System boundaries according to the functional units (FUs): in P1 the FUs are the delivery one metric tonne (t) of fishmeal or fish oil at the gate of the plant; in P2 the FU is the processing of 1 t of raw material entering at the floating terminal of the plant

3. LCI

3.1. Life cycle inventories

The land occupation is quite large (e.g. > 34 000 m² for Plant 1) because, in addition to the settlement of the plant itself, the plant must have a large storage area, sometimes cemented (Plants 2 and 3) sometimes gravelled (Plant 1). The total number of items of the LCI is presented in

Table 4, whereas the major flows of material and energy in the plants are summarized in **Error! Reference source not found.**, using the value of 30 years for lifespan of the factories.

Table 4: Number of items in the LCI of Plants 1 and 2, per phases of the LCA, and corresponding number of entries in SimaPro

LCA phase	This work LCI items (n)	This work Entries in SimaPro (n)	Danish lcafood LCI items (n)
Construction	258	25	0
Maintenance	100	20	0
Use	50	51	17
Total	409	90	17

3.2. LCI analysis

The annual quantities of raw material processed by the three plants are much lower than their potential processing capacity. Considering 240 potential working days at full time (that is 20 h of processing and 4 h of cleaning and preheating per day), Plants 1, 2 and 3 could have processed in theory 422 400, 547 200 and 24 000 t per year, respectively (and the whole Peruvian industry 44.9 million tons in 2009, based on a 9 350 t per hour capacity). This means that Plants 1 and 2 used 11% and 28% of their potential full capacities, respectively, and the whole sector 13% of it, reflecting the large overcapacity of the Peruvian fishmeal industry. In contrast Plant 3 used 40% of its potential full capacity, which is a reasonable value due to the high variability in time and space of the resource. This good performance of Plant 3 is mostly due to more regular supply, both in fish residues from DHC plants and in fresh fish from IUU anchoveta. Overcapacity of the traditional FAQ and modern plants (the dominant ones) is mostly due to the race for fish when the industrial fisheries were managed by a single quota and the annual duration of the number of fishing days felt below 50 days (Fréon et al., 2008). IVQs resulted in an increase of this duration to around 150 days and in a slow decrease of the capacity of the fleets, but not of the plants. As a result, the race to fish is now replaced by the race to buy fish from the freelance industrial wooden fleet (Fréon et al., 2014a).

The large overcapacity of the plants largely increases the LCI expressed by FU, especially the construction phase (Table 3). The maintenance phase is also affected, although to a lower extent, whereas the use phase is only indirectly affected by likely lower daily processing rates, as detailed below.

Fishmeal and fish oil yield rates mostly influence the process-based FUs. Because these rates are fluctuating (especially the oil rate) according to the environmental condition experience by the anchoveta, the rates were based on average data for the period 2002–2011 for better representativeness. The resulting values were 21.3% and 4.3% for fishmeal and fish oil yield respectively. These figures are lower than other values recently reported for Peruvian and foreign FMFO industries (Péron et al., 2010), mostly because Peru produces its FMFO nearly exclusively from whole fish and because Péron's reference period was shorter.

The construction of the plants required huge quantities of infrastructure material (bricks, cement, concrete) and of metals, including those known for their high environmental impact (chromium steel and copper). When those quantities were prorated by FUs along the life cycle of the plants, they become quite low but still significant, due to the underuse of the plants (Table 3).

The use and maintenance phases of the plant required large quantities of chemical products, particularly for inside cleaning the different devices every 20 h of use. Different types of paint were used during these two phases, resulting in airborne emissions of diluents. The LCI of the use phases of the plants are dominated by energy consumption, as it is the case for the fishery use phase (Avadí et al., 2014b; Fréon et al., 2014b, 2014c). The major sources of energy for the plants themselves are fossil fuels mostly used for heating (cooking of raw material, drying of fishmeal, evaporation plant) whereas the share of electricity is low (4.7% for Plant 1, 2.5% for Plant 2 and 1.7% for Plant 3). Most of this electricity (Plant 1: 76%; Plant 2: 93%) comes from the Peruvian grid (dominated by hydroelectric generation), the rest being self-generated (Table 5).

Emissions to the ocean resulted mostly from the phase use and were dominated by the large quantities of suspended solids (mostly fish residues) and the associated Biological Oxygen Demand after five days (BOD_5). Nitrogen outputs, also linked to suspended solids, were estimated from the Danish plant.

Table 5: Abridged inventory table of fishmeal production in Peru per process-based and output-based FUs, compared with a Danish plant in the first case

Type of FU	Inputs/outputs	Main items	Unit	Plant 2	Plant 1	Plant 3	Danish plant
Process-oriented FU (1 t raw material)	Inputs	Fuel use[a]	MJ	1,498	1,913	2,406	1,523
		Electricity[b]	kWh	20.6	13.8	15.3[c]	40.8
		Antioxidants	kg	0.17	0.25	0.10	0.08
		Concrete	L	13.7	1.97	2.54[c]	NA

		Sodium hydroxide	kg	0.59	0.58	0.68[c]	1.03
	Outputs	N	kg	0.35[d]	0.35[d]	0.35[d]	0.35
		Suspended solids	kg	3.70	6.92	7.69[c]	NA
		Oil and fat	kg	3.14	3.94	4.38[c]	NA
		BOD_5 or COD	kg	9.17[e]	17.8[e]	15.2[ef]	0.12[g]
Output-oriented FU (1 t fishmeal)	Additional inputs[h]	Fresh fish[i]	t	4.21	4.21	2.11	NA
		Fish residues[j]	t	0	0	2.75	NA
	Additional outputs[h]	Fish meal	t	1.00	1.00	1.00	NA
		Fish oil[k]	t	0.19	0.19	<0.19	NA

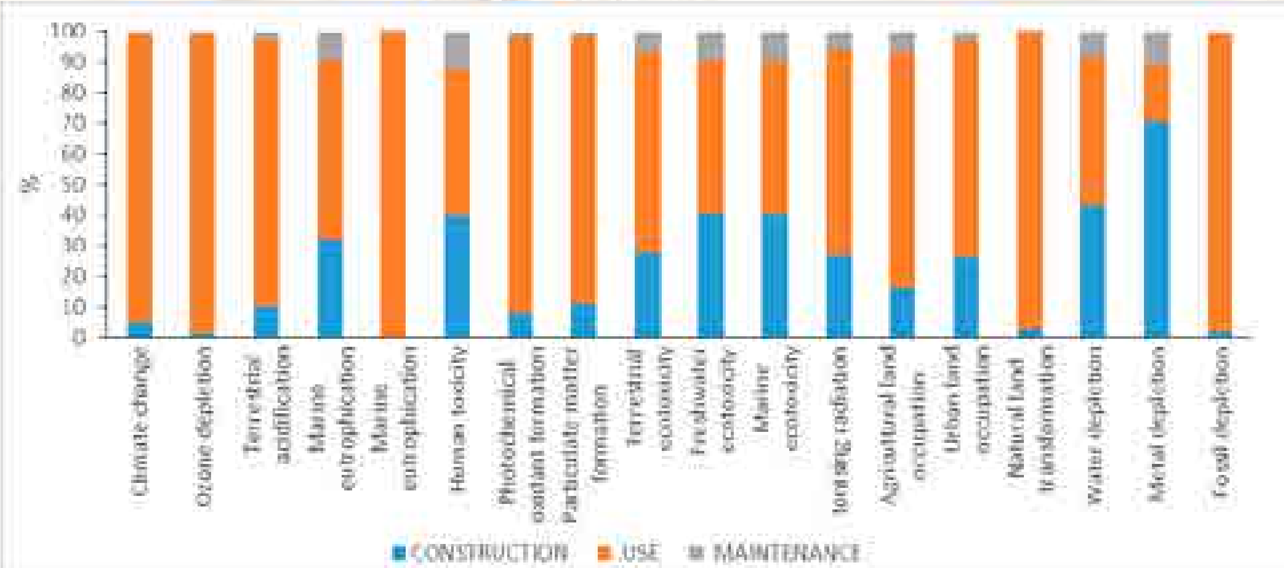
[a] Heavy fuel oil (R500) or natural gas used for heating (excluding fuel use for self-generated electricity and fishing). [b] Excluding self-generated. [c] Estimated from Plant 1. [d] No proper LCI data, Danish data used as proxy. [e] BOD_5. [f] From Plant 1 data, rescaled by yield rate. [g] COD. [h] In addition to above inputs, that must be rescaled by fish input. [i] Fish caught by the industrial steel fleet (81%) and the industrial wooden fleet (19%) for Plants 1 and 2, and the small- and medium-scale fleets (100%) for Plant 3. [j] Considering a 43% inclusion of fresh fish coming from IUU landing for reduction (range 30-50%), which results in a 50:50 ratio in fresh fish and fish residue in the origin of FM given their different yields (4.21 vs 5.5). [k] Allocation factor fishmeal:fish oil (mass-weighted gross energy content): 73:27.

The comparison between our LCIs and others, beyond the fact that our inventory is much more detailed, shows quite similar values regarding the use of fossil energy, but quite different results regarding other items (**Error! Reference source not found.**). Electricity consumption from the grid is twice lower in our study and this is only partly explained by the used of self-generated electricity. The use of chemical products inventoried in the Peruvian plants is much lower than those inventoried in the Danish plant, but this is certainly due to the fact that other descaling agents are used (and inventoried) in those plant.

4. LCIA

4.1. Process-based FUs

Because the Peruvian fishmeal production is increasingly dominated by Prime and Super Prime fishmeal, results of Plant 2 will be more detailed than the results of the other plants.
The dominant ReCiPe endpoints in the three Peruvian plants are by far human health and resources (not shown). As expected, most of the environmental impacts during the life span of fishmeal plants are due to the use phase. Nonetheless the construction and maintenance phases, largely ignored in other studies, contribute significantly. The average contribution of the use phase at the endpoint level is 87% in Plant 2, whereas the shares of the construction and maintenance phases are 10 and 2.5% respectively. Nonetheless, at the midpoint level, these contributions reach currently values of 10 to 40% in one or two of these two phases in (**Error! Reference source not found.**Figure **3**). As a result, the remaining contribution of the use phase varies from values as low as 19 to 77% in ten midpoint impact categories of ReCiPe. This difference in the relative importance of the use phase is due to the weighting factors used in the ReCiPe midpoints.



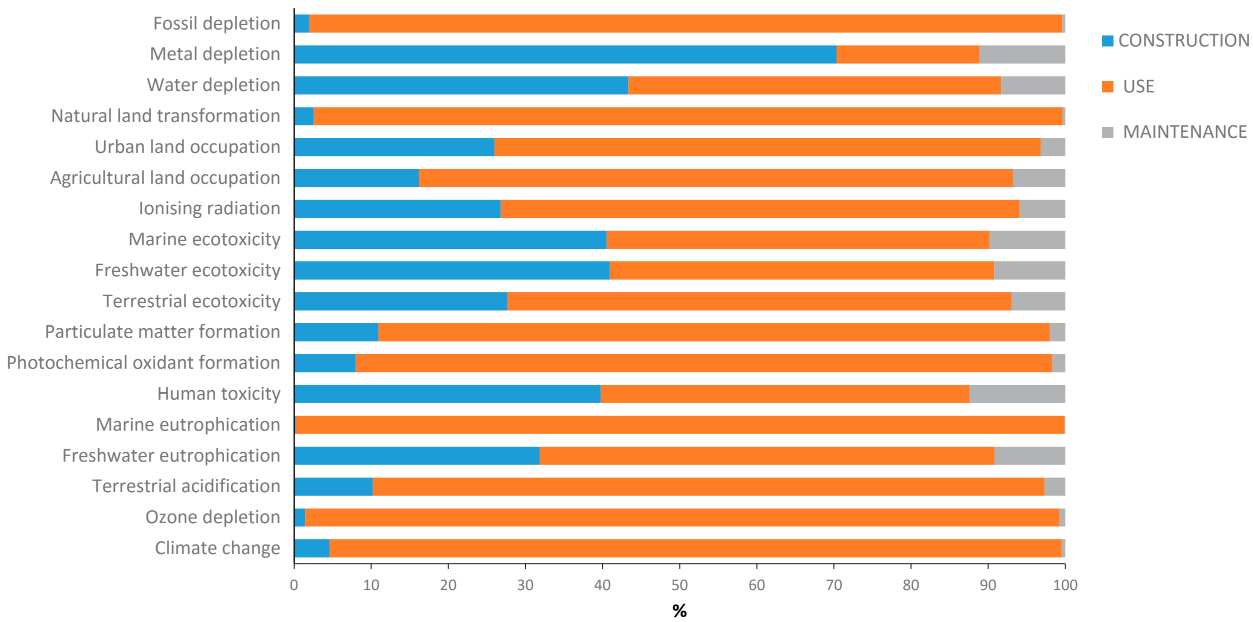


Figure 4: Fishmeal plant 2 LCA midpoint environmental impacts using the ReCiPe method. The functional unit is the processing of one t of raw material

Within the use phase, fuel use (mostly natural gas) dominates most of the midpoint impact categories, with the notable exceptions of marine eutrophication (where ocean waste dominates), freshwater eutrophication, agricultural land occupation and water depletion. The dominance of fuel use in industrial processes is a common finding (e.g. Hall and Howe, 2012). This dominance is even stronger in Plants 1 and 3 (not shown) than in Plant 2, due to the use of heavy fuel which is more impacting than natural gas. As a result, the relative importance of the use phase is higher in Plants 1 and 3 than in Plant 2.

The construction phase of Plant 2 is dominated in most midpoint categories (not shown) by the impact of concrete fabrication, the manufacturing of metals and the fabrication of unalloyed steel (cast iron) and chromium steel.

The maintenance phase is dominated by the impact of chemical products (not shown). Among them, those coming first in many midpoint impact categories are chlorine dioxide, epoxy paint and a variety of inorganic chemicals products used for cleaning. Copper also have a relatively strong impact.

The comparison of the environmental impacts of the three plants at the midpoint levels shows that Plant 2 is the cleanest in nearly all impact categories, Plant 3 the less environmental friendly, whereas Plant 1 falls in between (**Figure 5**:). The interpretation of these results is straightforward for most categories. First, Plant 2 benefits from the use of natural gas as its main energy source whereas, Plants 1 and 3 use heavy fuel. Second, Plant 2 average working hours per annum are double than those of Plant 1, which result in a lower impact per FU in the construction and maintenance phases, as explained earlier. Third, there are certainly economies of scale along the life cycle that benefit to Plant 2 and largely disadvantage Plant 3. In order to refine this comparison, we simulated the life cycle of Plant 1 using natural gas instead of heavy fuel. Because the requested changes in the capital goods are negligible, there were ignored. In all impact categories except metal depletion, the move to gas supply results in substantial or large decreases of impact. As a result, the impacts of the simulated Plant 1 falls most of the time in-between those of Plant 1 (original) and 3, or close to those of Plant 2.

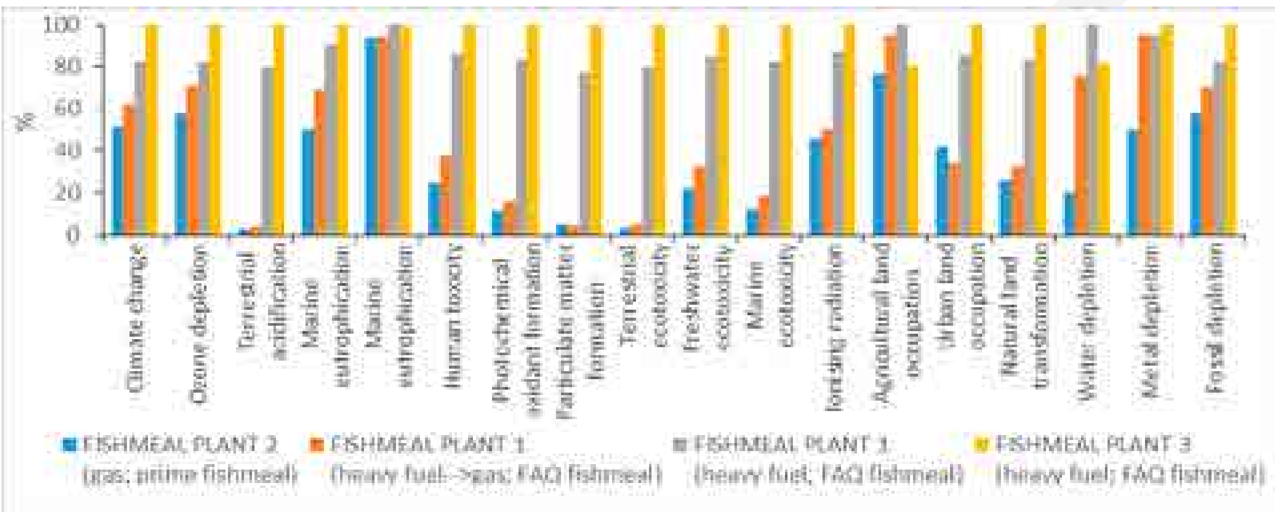


Figure 5: Comparison of LCA midpoint environmental impacts of the three fishmeal plants (with addition of a simulation of Plant 1 using natural gas) using the ReCiPe method. The functional unit is the processing of one t of raw material

The comparison between our LCIA and other work is hindered by large difference in the LCIs, mostly due to the use of different cut-off rules. The effects of this difference in LCIs on the LCIA are evidenced by comparing Plant 2 current results with simulated results based on the same limited number of entries as the Danish LCI. The ReCiPe single score of Plant 2 is 20% higher when its LCI is detailed than when it is as coarse as the Danish one. This is partly due to the absence of the construction and maintenance phase in the latter case, but also to the lack of several items in the inventory of the use phase. It worth noting that at the midpoint level this comparison shows increases >100% in the categories human toxicity, freshwater ecotoxicity, marine ecotoxicity, urban land occupation and water depletion, and >470% in metal depletion (not shown).

Plant 2 LCIA results resulting from the simulation of a paucity of data were compared with the Danish plant results, assuming that its heat production uses natural gas. The ReCiPe single score of the Danish plant is 28% higher than the score of Plant 2 when using the same coarse LCI. This result is surprising because the two plants use similar quantities of fossil energy, the major source of impact in Plant 2. The LCIA of the Danish plant (not shown) shows that the share of electricity represents nearly 30% of the impact of its direct energy consumption, versus 9% for Plant 2. This is not only because the Danish plant use twice the amount of electricity than the Peruvian plant. It is also because the Danish electricity production is more impacting than the Peruvian one due to the relative contribution of coal–powered generation.

4.2. Output-based FUs

The share of anchoveta supply in the ReCiPe single score impact of Plant 2 life cycle is 49%. The dominant endpoints are by far human health and resources (not shown). As expected, the relative contribution of the construction and maintenance phases of the plant decreases substantially in most impact categories when considering the output-based FUs. At the midpoint level (not shown), all these contribution are lower than 15%, except for water depletion (20%), ionising radiation and human toxicity (16% each). As a result the remaining contribution of the use phase varies from 76 to 100%.

Within the use phase, the supply of raw material by the two industrial fleets dominated most of the midpoint impact categories in Plant 2 (not shown), followed by fuel use, with the notable exceptions of marine eutrophication. It is worth noting that fuel use impact also dominates in most categories of the supply of raw material (Avadí et al., 2014b; Fréon et al., 2014b, 2014c). As a result, fuel use is by far the most impacting issue in the output-based FUs.

The comparison of the relative environmental impacts of the Peruvian plants at the endpoint levels (not shown) are similar to those obtained using the process-based FU.

4.3. Towards a cleaner production

The environmental benefit of using natural gas instead of heavy fuel as energy source in Plant 1 can be quantified first by the single score of the process-based FUs that shows a decrease of 41%, and second at the midpoint level were all categories decreased by more than 24%, except metal depletion, agricultural land occupation, marine eutrophication and ozone depletion (Comparison of LCA midpoint environmental impacts of the three fishmeal plants (with addition of a simulation of Plant 1 using natural gas) using the ReCiPe method. The functional unit is the processing of one t of raw material). Similarly, the benefit resulting from the production of Prime fishmeal instead of FAQ is obvious, although not precisely quantifiable from Comparison of LCA midpoint environmental impacts of the three fishmeal plants (with addition of a simulation of Plant 1 using natural gas) using the ReCiPe method. The functional unit is the processing of one t of raw material because, even after simulation of Plant 1 using natural gas as Plant 2, the production of these two commodities still comes from two different plants with different capacities, etc.

It is noteworthy that when a plant line works at its average processing rate, as it was mostly the case for Plants 2 and 3, but less true for Plant 1 in 2009, the fuel consumption is optimal. In contrast, when a line does not produce fishmeal but expect fish delivery for the next days, it carries on consuming fuel either for keeping warm its major equipment (cooker and drier) or for preheating them at the end of the daily 4-hour cleaning. Durand (2010) showed that when the actual daily processing rate increases from 60 to 138 t/h, fuel use decreases from 8.0 to 5.7 GJ per t of fishmeal produced. These results, although based only on 9 data points, show that the processing overcapacity combined with the increased fishing season (which generates difficulties to optimize daily processing rate), result in a substantial waste of energy.

Cleaner production and improved quality of final products can be obtained by chilling the fish on board when necessary. Oldest plants could benefit from renovation aimed at reducing energy lost by recycling the steam, eliminating steam leaking, and from increase descaling frequency to limit inhibition of heat transfer.

Finally, a better processing of blood water should result in reaching the legal maximum limits regarding the emissions of suspended solids, oil (result not shown) and BOD, which is not the case presently.

5. Recommendations and conclusion

This is, as far as we know, the first detailed LCA of fishmeal plants in the world, beyond existing screening LCAs. The LCIs of the construction and maintenance phases represented by far the heaviest work, although their corresponding environmental impacts were much lower than that of the use phase (87% of the ReCiPe single score, dominated by fuel use), which is a common finding in LCAs of industrial processes. The share of these two phases in the Peruvian case, particularly the construction one, is exacerbated by the processing overcapacity. As a result, these combined shares can reach 23 to 81% in some midpoint impact categories for Plant 2. Ideally, future studies on fishmeal and residual fishmeal plants should include not only a screening of the construction and maintenance phases, but also an improvement of the LCI of the use phase. According to our simulation, the Danish plant LCA screening, the most documented one available, is likely to have underestimated its environmental impact by more than 15% at the single score level, and by more than 100% in some midpoint impact categories.

There is room to decrease the environmental impact of this industry (use of natural gas instead of heavy fuel, reduction of overcapacity, modernisation of the oldest plants, production of higher fishmeal quality, improvement of sanitary condition, etc.). Because the use of natural gas instead of heavy fuel as the main source of energy results in large decreases of environmental impacts (Comparison of LCA midpoint environmental impacts of the three fishmeal plants (with addition of a simulation of Plant 1 using natural gas) using the ReCiPe method. The functional unit is the processing of one t of raw material), it is recommended to favour this move by extending the natural gas network all along the Peruvian coast. Presently this network covers only a fourth of the Peruvian coast line. Projects to extend this network exist but suffer from delays. Similarly, the move from the production of FAQ fishmeal to the production of Prime fishmeal, already started, should continue to be encouraged by the legislation. These two measures are beneficial both from the environmental and economic points of view. Regarding overcapacity, if it was decreased by a factor two, the share of the construction phase would decrease by about the same amount. A final recommendation for the Peruvian industrial sector is to enforce the present policy regarding management and sanitary conditions in order to address "black fishing" and under-reporting issues, illegal and unregulated fishmeal plants in operation and the lack of compliance with environmental regulations (although recent progresses in these domains have been observed).

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