Intelligent Fish feeding through Integration of ENabling technologies and Circular principles

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1 Introduction

In general, life cycle costing (LCC) is a process of summarising the costs incurred over the life cycle of a product. The SETAC-Europe Working Group in Life Cycle on Life Cycle Costing has defined three types of LCC: conventional, environmental, and societal (Hunkeler et al. 2008). Environmental LCC and societal LCC differ from conventional LCC in various ways, including the definition of the term life cycle. When applied to conventional LCC, the term usually refers to the market life cycle of the product. The market life cycle of a product has different stages, beginning with its introduction upon the market, a stage of growth followed by a stage of maturity, and then an eventual decline. When performing environmental LCC, a product life cycle is defined within the context of its value chain, which includes all processes that are required to create and deliver a product. This may include end of life processes, such as the disposal of a product subsequent to its use. Environmental LCC is an emerging tool that is intended to be compatible with LCA as part of an approach towards understanding the relationships between the '*three pillars of sustainability*': the environment, society, and economy.

Although the practice of LCC is not new, environmental-LCC is a relatively new occurrence in its evolution. There is no standardisation of E-LCC methodology (which is, arguably, not sufficiently developed to enable or warrant such standards), although guidelines have been produced by Hunkler et. al (2008) and the Society of Environmental Toxicology and Chemistry (Swarr et al., 2011). These guidelines will be consulted throughout the process, but not necessarily adhered to with consistency.

The chosen approach for this study is based on the premise that the life cycle environmental impacts of economic production are negative externalities. Internalisation of environmental impacts might be possible if they can be monetised.

2 Environmental Life Cycle Costing Goal and Scope Definition

2.1 System boundaries

Harmonisation of the LCA and LCC requires that the life cycle is defined within the context of the value chain. Thus, the system boundaries must consistent between the LCA and LCC.

To the most practical and appropriate extent, the economic focus of the LCC will be maintained whilst adhering to the required consistency. Whereas the methods of impact assessment may differ between the LCA and LCC, the system boundaries are to be the same. Such intentions notwithstanding, there are challenges to be overcome. As described in deliverable 4.6, it is expected that the product value chains will be assessed only as far as the farm gate. This is a potential problem because the monetary value of a product is defined as its market value. This means implies that process occurring downstream of the farm gate should be assessed, possible including the costs of product marketing.

2.2 Coproduct allocation

Coproduct allocation based upon the monetary value of product flows (Guinée et al. 2004) is a practice that is somewhat controversial, and it has been argued that it is inappropriate for LCAs of food products (Pelletier and Tyedmers 2011). However, there are arguments supporting its use (e.g., Weinzettel, 2012) and it is commonly applied in practice. Economic allocation has been used for this study, and the method used to apportion the inputs and outputs between coproducts is demonstrated started in the following example, where it is assumed that allocation must be performed between two coproducts, 'coproduct*a*' and 'coproduct*b*':

Eq.1.

Allocation factor coproducta = monetary value coproductamonetary value coproducta + monetary value coproductb

Eq.2.
Monetary value of coproduct = monetary value per quantity of coproduct X coproduct quantity

2.2.1 Internal costs

Assuming that system boundaries and the functional unit allocation are consistently applied, the flows for which costs must be determined as part of the LCC are mostly same as those complied within the LCA-inventory. There are, however, exceptions, and these must be determined separately if they are to feature within the LCC. Perhaps the most obvious of these, in this project at least, is labour, which can be expected to incur a non-negligible cost Table 1. presents the principle flows for which costs must be determined. Any additional flows will be identified through the process of compiling the inventory, assisted beforehand through the production of flow diagrams depicting the relevant processes of the value chain.

2.2.2 External costs

Value chains have effects that are not planned objectives that motivate production. Such effects are referred to as **externalities**, and within the context of economics they can be considered as an example of market failure, as they are not presented in the market price of a good. Environmental impacts are externalities of an obvious relevance to environmental-LCC. Monetisation of these externalities – the expression of environmental impacts in monetary terms, in effect, internalises them as costs (assuming the impacts are not beneficial) incurred through the course of producing and bringing a good to the market. This concept is central to the polluter pays principle, the eventual implementation of which within the European common market is by Article 191 of the Treaty of the Functioning of the European Union (2016). According to Hunkeler et al. (2008), the externalities to be included in an environmental-LCC should be limited to those which can be expected to incur a monetary cost within the decision-relevant future. The emissions of greenhouse gases definitely fit this definition: various countries within the EU levy a carbon tax (other gases) and all member states are participants of the EU Emissions Trading System. Emissions of these gases and their potential contribution to climate change will be quantified as part of the LCA performed in the iFishIENCi project. The monetary value of these flows (*viz.* emissions) may be considered as being equivalent to the costs incurred by their taxation. These costs can be compared to the costs of their complete or partial abatement (e.g., the use of flue gas scrubbing technology).

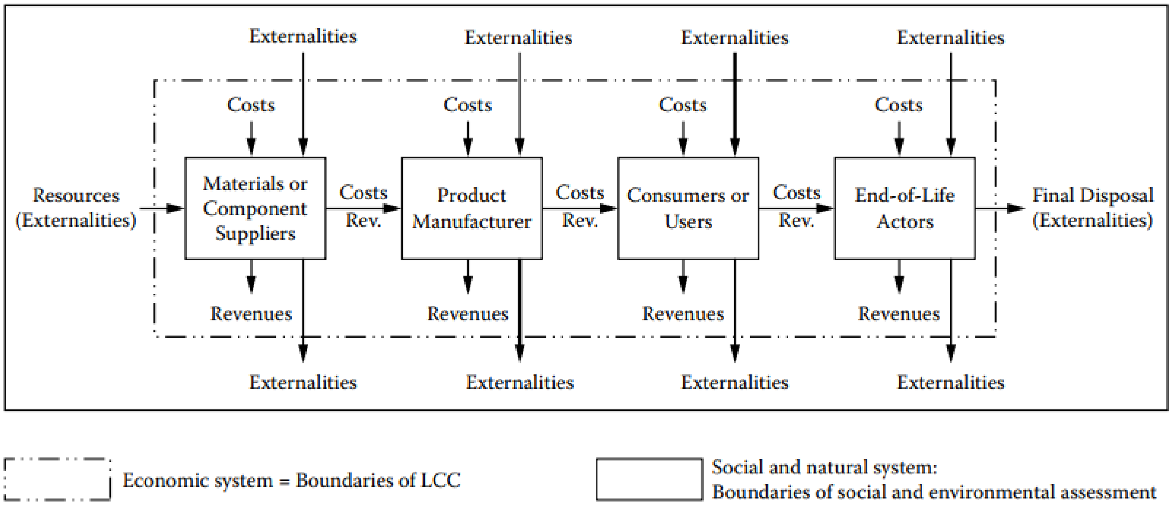

Figure 1. Stages of the value chain assessed by environmental-LCC. Although consumer use and product end-of-life phases are depicted, they may not be assessed by the iFishIENCi project. The stages appear different from the stages included in the life cycle assessment, but the underlying processes are the same. The stages must not necessarily be aggregated according to this figure, as long as the system boundary of the LCA and LCC are equal.

Within the context of welfare and environmental economics, impacts cause damage by reducing the availability of non-market goods, the monetary value of which can estimated using measures of marginal willingness to pay (WTP). In this project monetary valuation has been used as basis for the weighting of life cycle impacts. It is not within the project scope to determine the marginal value society gives to various environmental impacts. However, CE Delft has collated values intended to be representative of the EU28 in the year 2015. CE Delft have used these values as weighting factors for a selection of emissions, midpoint impact categories and endpoint damage categories. The ReCiPe 2008 impact assessment model (hierarchical perspective) provides the methodological basis for the characterisation of midpoint impacts, apart from the category '*climate change*,' which is calculated according to the procedure recommended by the Intergovernmental Panel on Climate Change (Goedkoop et al. 2009). The resulting value-weighted midpoint assessment model was applied to the life cycle inventories described in Deliverable 4.6. The factors used for the weighting of each impact category are shown in Table 1.

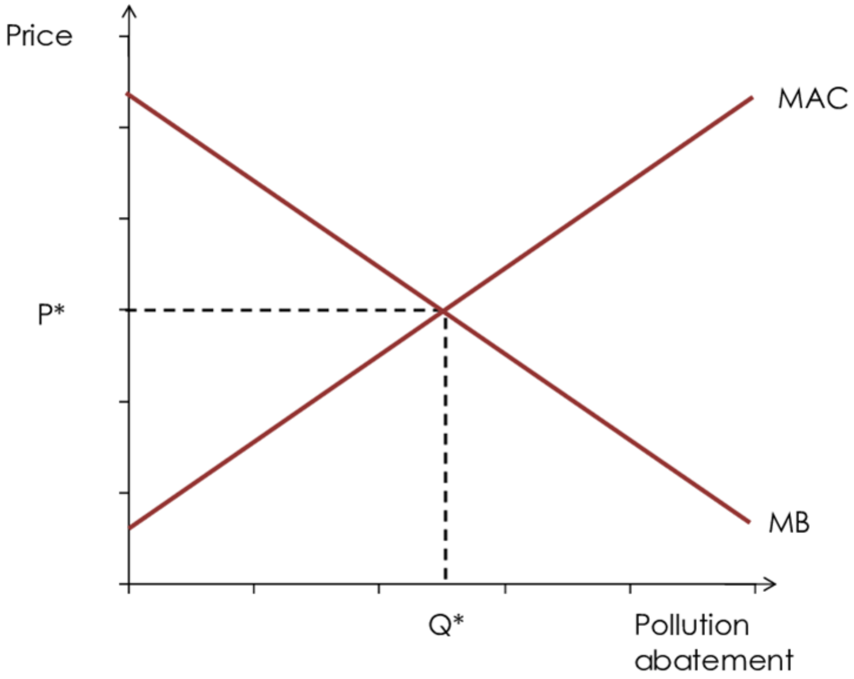

Figure 1*. Social optimum level of pollution abatement. As the marginal cost of pollution abatement (MAC) increases, the marginal benefit (MB) to society decreases. The pareto-optimal level of pollution occurs at the intersection of MAC and MB. The monetary price (cost) of increasing pollution abatement beyond the pareto-optimal exceeds that of the monetary price society places upon the resulting improvement of environmental quality. Source: Kettner et al. 2011.*

Table 1. Characterisation factors (units) and weighting factors (price) for each midpoint impact category of the CE Delft Environmental Prices method.

Impact category	**Unit**	**Price as weighting factor**
Climate change	€/kg CO2-eq.	€0.06
Ozone layer depletion	€/kg CFC-eq.	€123
Human toxicity	€/kg 1,4 DB-eq.	€0.09
Photochemical oxidant formation	€/kg NMVOC-eq	€1.15
Particulate matter formation	€/kg PM10-eq.	€39.20
Ionizing radiation	€/kg kBq U235-eq.	€0.05
Acidification	€/kg SO2-eq	€7.48
Freshwater eutrophication	€/kg P-eq.	€1.86
Marine eutrophication	€/kg N.	€3.11
Terrestrial ecotoxicity	€/kg 1,4 DB-eq.	€8.69
Freshwater ecotoxicity	€/kg 1,4 DB-eq.	€0.04
Marine ecotoxicity	€/kg 1,4 DB-eq.	€0.01
Land use	€/m2a.	€0.13

3 Catfish grow-out in RAS

In general, the presence of cost incurring inputs such as energy and equipment are usually higher per unit product for high technology RAS based cultivation than it is for flow through operations or those located in marine waters (which depend upon the natural ecosystem to supply oxygenated water). Thus, the relative contribution of feed is often lower for RAS. The successful implementation of RAS technology to produce fish requires that it can provide a financially viable alternative to competing systems, and any benefits of RAS production (such as those potentially offered through the degree of containment they offer) must not be realised at the expense of unacceptable financial trade-offs. Fish species that can be cultivated at high densities may be produced with greater energetic efficiency (greater number of fish per unit energy consumption), although a linear relationship is unlikely to characterise such improvements. African catfish are species that can be cultivated at densities which may appear startling (≥350 kg/m^3) when compared to those typical of species such as trout, seabream, and salmon. However, despite this apparent advantage, African catfish do not command a high market price in Europe. In Hungary, the average, farm gate live-weight market price according to ___ was 1.92 EUR per kilogram. The total sum of direct and indirect costs of catfish produced in RAS (Table 3) is calculated to be 3 EUR per kg, delivering a net profit of -0.95 and a resulting net margin of -49.3%. This is a clearly unviable enterprise should these values hold true. Feed costs, followed by the cost of electricity, contribute the most towards total costs (50.58% and 19.88% respectively). The prospects for financial viability and sustainability require an increase in revenue combined with a reduction in feed and energy-related costs. Operational, commercial production of African catfish in RAS does supply fish to the European market, so the results of this case study should be interpreted as cautionary rather than conclusive. However, it can be anticipated that the internalising of negative externalities does not improve this situation. Table 4 shows the budget statement for catfish RAS production when potential life cycle environmental impacts are internalised. This raises the sum of costs to 6.57 EUR per kilogram of live-weight fish at the farm gate and reduces the net profit to -4.65 with a net margin of -242.23. Evidently, the cost of environmental impacts is not cheap. However, not all impacts need to be included. Society does not have a consensus on what environmental impacts an industry (or producer) should be expected to pay for or neither how much that cost may be. However, the European Commission initiative to develop product environmental footprint methods for application to product categories may provide a good starting point, and perhaps in the future may be combined with economic-based weighting values.

Table 2. *Budget statement for the production of African catfish in a Recirculation Aquaculture System*

Revenue	**€/kg fish**	**€/yr.**	**% of total revenue**	
Whole fish farm-gate	1.92	1920000	100	
Variable costs (VC)	**€/kg fish**	**€/yr.**	**% of total VC**	**% of TC**
Juveniles	0.14	140000	5.98	4.88
Feed	1.45	1450000	61.97	50.58
Electricity	0.57	570000	24.36	19.88
Staff	0.18	180000	7.69	6.28
Total	*2.34*	*2340000*	100	*81.63*
Fixed costs (FC)	**€/kg fish**	**€/yr.**	**% of total FC**	**% of TC**
Depreciation	0.49	490000	93.04	17.09
Insurance	0.00965	9650	1.83	0.34
Overheads	0.027	27000	5.13	0.94
Total	*0.52665*	*526650*	100	*18.37*
Total cost (TC)			**€/kg fish**	**€/yr.**
Sum of all costs			3	2866650
Profit			**€/kg fish**	**€/yr.**
Net profit			-0.95	-946650
Net margin			-49.30	-49.30

Table 3. Budget statement for the production of African catfish in a Recirculation Aquaculture System, including the internalisation of environmental negative externalities.

Revenue	**€/kg fish**	**€/yr.**	**% of total revenue**	
Whole fish farm-gate	1.92	1920000	100	
Variable costs (VC)	**€/kg fish**	**€/yr.**	**% of total VC**	**% of TC**
Juveniles (seed)	0.14	140000	5.98	2.13
Feed	1.45	1450000	61.97	22.07
Electricity	0.57	570000	24.36	8.67
Staff	0.18	180000	7.69	2.74
Total	*2.34*	*2340000*	100	*35.61*
Fixed costs (FC)	**€/kg fish**	**€/yr.**	**% of total FC**	**% of TC**
Depreciation	0.49	490000	93.04	7.46
Insurance	0.00965	9650	1.83	0.15
Overheads	0.027	27000	5.13	0.41
Total	*0.52665*	*526650*	100	*8.02*
Externalised costs (EC)	**€/kg fish**	**€/yr.**	**% of total EC**	**% of TC**
Climate change	0.341	341000	9.21	5.19
Ozone depletion	9.00E-05	90	0.0024	0.00
Terrestrial acidification	0.164	164000	4.43	2.50
Freshwater eutrophication	0.018	18000	0.49	0.27
Marine eutrophication	0.341	341000	9.21	5.19
Human toxicity	0.259	259000	6.99	3.94
Photochemical oxidant formation	0.016	16000	0.43	0.24
Particulate matter formation	0.344	344000	9.29	5.24
Terrestrial ecotoxicity	0.132	132000	3.56	2.01
Freshwater ecotoxicity	0.004	4000	0.11	0.06
Marine ecotoxicity	0.001	1000	0.027	0.02
Ionising radiation	0.107	107000	2.89	1.63
Agricultural land occupation	0.317	317000	8.56	4.82
Urban land occupation	1.66	1660000	44.82	25.26
Total	*3.70409*	*3704090*	100	56.37
Total costs (TC)			**€/kg fish**	**€/yr**
Sum of all costs			6.57	6570740
Profit			**€/kg fish**	**€/yr**
Net profit			-4.65	-4650740
Net margin			-242.23	-242.23

The valued impacts featured in Table 4 can be further explored. Figure 4 shows the contribution of feed provision, infrastructure, energy consumption, and nutrient emissions towards each of the environmental impact categories. The use of a common indicator value (Euros) allows the aggregation of these impacts into a single for each process. Figure *5* shows the aggregate weighted impacts for, again, feed provision, infrastructure, energy consumption, and nutrients emitted through water discharges. It is evident from Figure 4 that urban land occupation incurs the greatest cost and that the supply of feed is responsible for the majority of this. This will be explored in more detail in the following section.

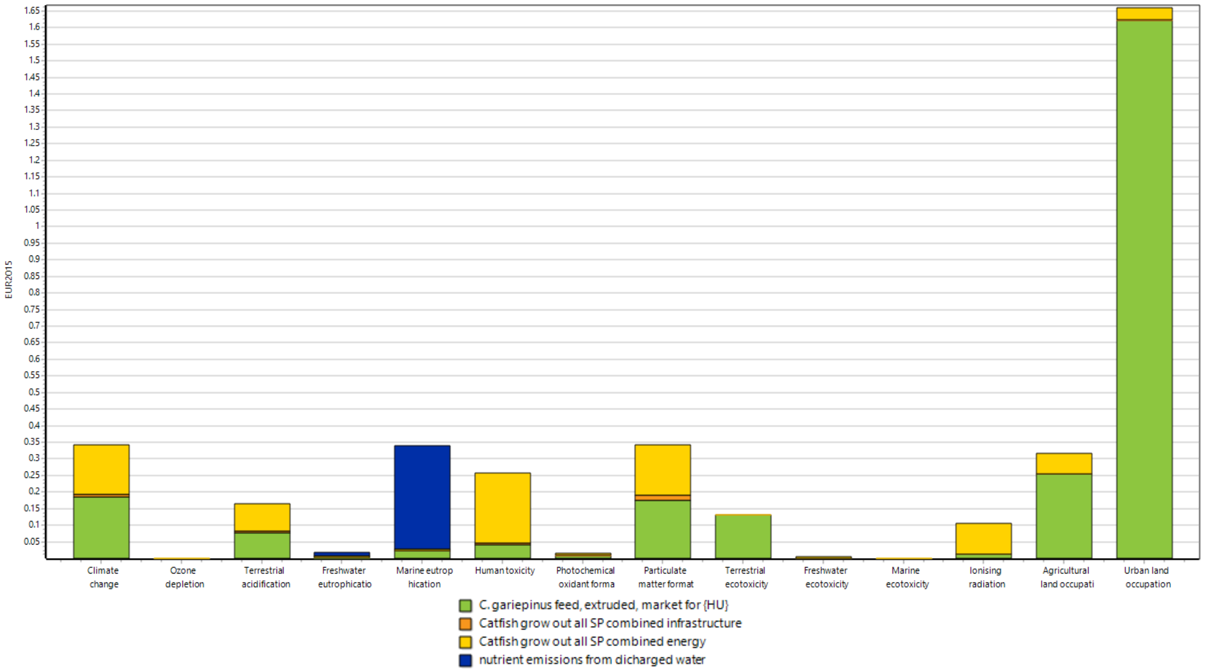

Figure 2. Weighted characterised impact results for the production of catfish in RAS. Calculated using the Environmental V.1 method.

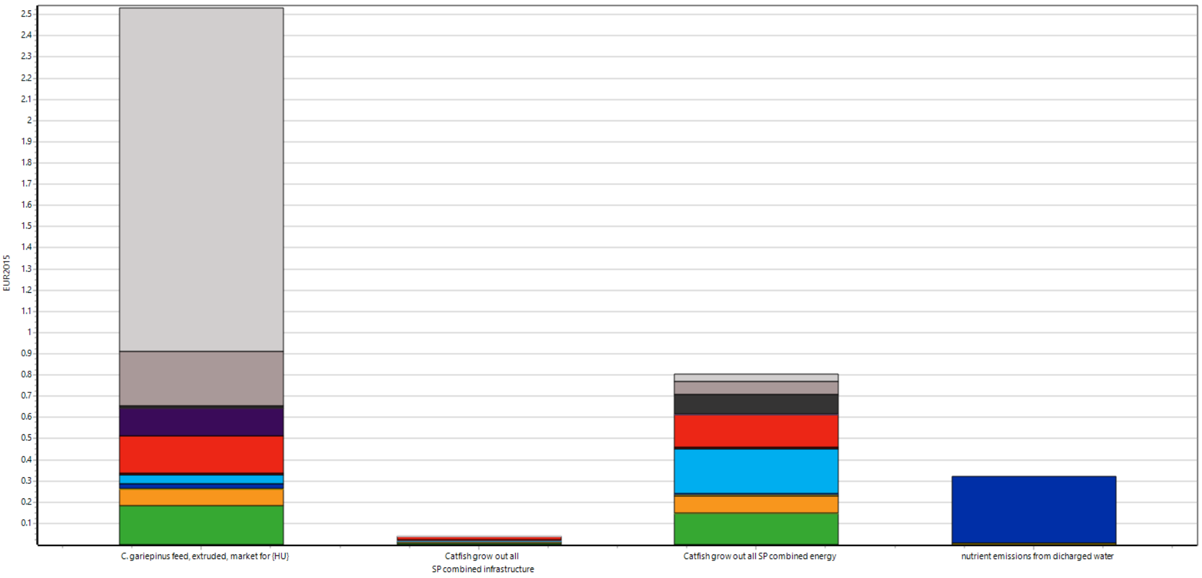

Figure 3. Aggregated, weighted characterised impact results for the production of catfish in RAS. Calculated using the Environmental V.1 method.

Table 4. Weighted characterised impact results for the production of catfish in RAS. Calculated using the Environmental V.1 method.

Impact category	Total (EUR)	% of total			
		Feed (standard diet)	Infrastructure	Energy	Discharged water
Total	3.703	68.361	1.145	21.768	-
Climate change	0.341	54.033	2.763	43.204	-
Ozone depletion	0.000	36.160	3.324	60.517	-
Terrestrial acidification	0.164	46.466	3.278	50.257	-
Freshwater eutrophication	0.018	9.883	0.293	37.544	52.281
Marine eutrophication	0.341	6.954	0.043	0.978	92.025
Human toxicity	0.259	16.079	2.164	81.757	-
Photochemical oxidant formation	0.016	51.138	6.390	42.472	-
Particulate matter formation	0.344	51.043	4.309	44.648	-
Terrestrial ecotoxicity	0.132	98.797	0.401	0.802	-
Freshwater ecotoxicity	0.004	21.465	5.383	73.152	-
Marine ecotoxicity	0.001	20.720	5.559	73.721	-
Ionising radiation	0.107	11.769	0.541	87.690	-
Agricultural land occupation	0.317	80.437	0.143	19.420	-
Urban land occupation	1.660	97.653	0.249	2.099	-

4 Catfish feed

Feed production is frequently cited as representing a major, if not the largest, financial cost of aquaculture of grow-out operations. The relative magnitude of this cost compared to others tend to differ across system types, as discussed in the above section. Data describing the financial cost costs and revenue of feed production are not easy to come by. For this reason, data describing the variable costs of catfish feed production was based upon Suleiman and Rosentrater (2018). The source describes data for the production of a generic extruded finfish diet and does not refer to the specific production of catfish feed. Nor does it refer to specifically to one or more existing production facilities, rather it is based upon data and extrapolations from a pilot scale extrusion operation. Thus, the data are likely to be associated with various sources of qualitative and quantitative uncertainty when used within the context of this study (something which the publication by Sulieman and Rosentrater, 2018, was never intended to be used for). The data from this publication was modified by converting USD to EUR, and it was assumed that 40,000t/yr. feed is produced (this later value being representative of commercial production). With no data being made available for fixed costs, depreciation was assumed to be equivalent to that of the sludge valorisation process and overheads were calculated as 15 of labour costs. Again, these values are likely not representative of a real-life situation, rather they are used a proxy value in the absence of a more suitable data set. The resulting total cost of production is 0.88 EUR a per kilogram, this being lower than the assumed sale price of 1.16 EUR/kg feed. In this case the resulting net profit is 0.28 EUR/kg with a net margin of 75%.

Table 5. Budget statement for the production of African catfish feed.

Variable costs (VC)	**€/kg**	**€/yr.**	**% of total VC**	**% of TC**
Electricity	0.0000658	2632	0.01	0.08
Water	0.0000188	752	0.0024	0.02
Labour	0.0813006	3252024	10.3007	93.21
Raw ingredients	0.7048308	28193232	89.3015	808.09
Maintenance and repairs	0.00282	112800	0.3573	3.23
Others	0.000235	9400	0.0298	0.27
Total	*0.789271*	*31570840*	100	*93.31*
Fixed costs (FC)	**€/kg**	**€/yr.**	**% of total FC**	**% of TC**
Depreciation	0.08	8800	86.02	8.56
Overheads	0.012195	1430.378	13.98	1.39
Total	*0.09*	*10230.378*	100	*9.95*
Total cost (TC)			**€/kg**	**€/yr.**
Sum of all costs			0.88	31581070

The effect of internalising hitherto externalised costs can be seen in Table 5. The sum of costs is increased to 2.87 EUR a kg (an increase of 1.98 EUR), and at the assumed sales price of 1.62 EUR, the product of feed would not be profitable. It could be possible to increase the price of feed. However, this would likely be past on to the cost of catfish production, which may already have a tight profit margin. Figure *4* shows the contribution of each process of feed production towards the total cost of each impact category. Again, it must be stressed that variable and fixed costs used in the budget statement may not be representative of a realistic situation, and so it cannot be satisfactorily confirmed according to this study that the costs of internalising negative environmental externalities cannot be absorbed without unduly exceeding revenues. Consistent with the results for catfish RAS production, the costs incurred by urban land occupation overshadow those of other impact categories. This was expected, as feed was the dominant contributor to this category. Such a dominant position held by one impact category may seem disproportionate and so this will be investigated further. Figure 4 shows the value-weighted impacts for the production of conventional catfish feed. Soybean meal is the greatest contributor, followed by hydrolysed feather meal. More than 99% of the contributions for both of these ingredients comes from the eco-invent process 'treatment of garden biowaste, home composting in heaps' (an input to the production of Brazilian soybean, an input to soybean meal production). The extent to which this reflects the real-life scenario for the treatment of soybean production co-products is questionable, especially since it is responsible for such a significant influence upon the results. Urban land-would not necessarily be expected to be used for the composting of agricultural co-products in Brazil. If the cost of urban land occupation (1.29 EUR/kg) is removed, the total cost of production is 1.58 EUR and the net profit is 0.04 EUR a kilogram of feed. This is not enough profit to make to convince a would-be investor to consider this a safe bet. But if the costs of production can be lowered (and this may well be realistic), there may be some scope to absorb externalised costs, especially if the only one or a few of the suit are impacts are to be internalised.

Table 5. Budget statement for the production of African catfish feed, including the internalisation of environmental negative externalities.

Variable costs (VC)	**€/kg**	**€/yr.**	**% of total VC**	**% of TC**
Electricity	0.0000658	2632	0.01	0.002
Water	0.0000188	752	0.00	0.001
Labour	0.0813006	3252024	10.30	2.831
Raw ingredients	0.7048308	28193232	89.30	24.542
Maintenance and repairs	0.00282	112800	0.36	0.098
Others	0.000235	9400	0.03	0.008
Total	*0.789271*	*31570840*	100.00	*27.48*
Fixed costs (FC)	**€/kg**	**€/yr.**	**% of total FC**	**% of TC**
Depreciation	0.08	8800	86.02	2.61
Overheads	0.012195	1430.37796	13.98	0.42
Total	*0.09*	*10230.378*	100	*3.04*
External costs (EC)	**€/kg**	**€/yr.**	**% of total EC**	**% of TC**
Climate change	0.14	5610905.33	118606.92	4.88

Ozone depletion	0.00002	936.49	19.80	0.001
Terrestrial acidification	0.06	2275653.18	48104.22	1.981
Freshwater eutrophication	0.00	55569.11	1174.66	0.048
Marine eutrophication	0.02	755233.04	15964.60	0.657
Human toxicity	0.03	1208175.97	25539.20	1.052
Photochemical oxidant formation	0.01	230345.65	4869.19	0.201
Particulate matter formation	0.13	5174088.29	109373.20	4.504
Terrestrial ecotoxicity	0.10	4158350.27	87901.88	3.620
Freshwater ecotoxicity	0.00	26336.46	556.72	0.023
Marine ecotoxicity	0.00	4730.67	100.00	0.004
Ionising radiation	0.01	382770.81	8091.26	0.333
Agricultural land occupation	0.20	8147933.23	172236.24	7.093
Urban land occupation	1.29	51786726.5	1094701.07	45.080
Total	*2.00*	79817755	1687239	69.48
Total cost (TC)			**€/kg**	**€/yr.**
Sum of all costs			3	31581070

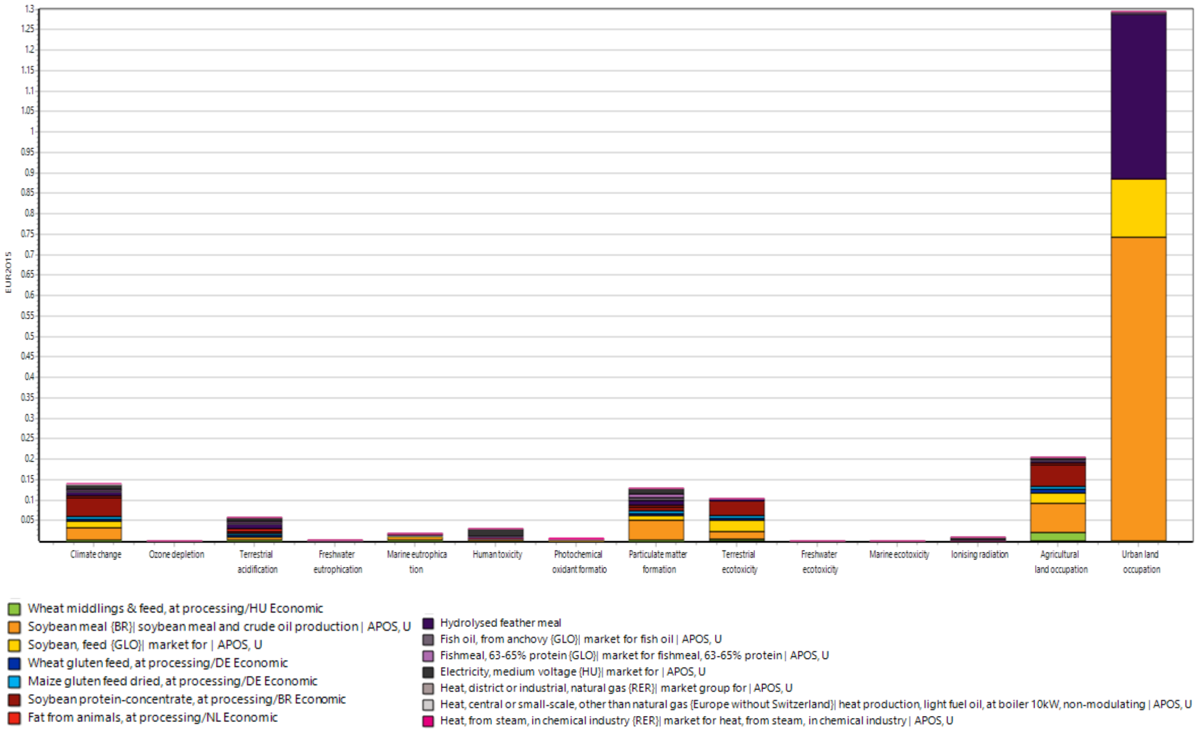

Figure 4. Weighted characterised impact results for the production of African carfishfeed. Calculated using the Environmental V.1 method.

5 Sludge valorisation

The cost of energy and water consumption to produce sludge was based upon the cost of energy (1.04 EUR/kWh) and water (assumed to be 1 EUR/m^3) in Hungary, the quantity of energy and water consumed according to the life cycle inventory for sludge valorisation. Labour was based upon the employment of two people each with an annual salary of 25,000 EUR per annum. For the pricing of capital goods, an attempt was made to upscale from laboratory scale to commercial scale, assuming the production of 117291.3kg of nitrogen per year. The total cost (not including internalisation of environmental externalities) is 839.92 EUR per kg of sludge. The values for energy and water consumption have been reduced by 75% as an attempt to account for a possible reduction in costs through economic of scale. However, despite this, the costs are still very high. Of course, when environmental externalities are absorbed, the situation is worse, with the total cost now reaching 970 per kg of N. Considering that the average price of commercially available nitrogen was calculated as being 1.92 EUR per kilogram, the cost of extracting nitrogen from sludge appears to be far from economically viable. However, the processes are still in the early stages of development. As system is upscaled improved efficiency may result through synergies between processes and reductions in system entropy. The recovery of nitrogen from sludge deserves continued research. Detailed modelling approaches may be employed to understand technological, biological, and economic bottlenecks in the extraction process at different scales of production.

Table 6. Budget statement for the extraction of nitrogen from aquaculture sludge, including the internalisation of environmental negative externalities.

Variable costs (VC)	**€/kg**	**€/yr.**	**% of total VC**	**% of TC**
Energy	838	98290109.40	99.91	99.77
Water consumption	0.33	38706.13	0.04	0.04
Labour	0.43	50000	0.05	0.05
Total	*838.7562891*	*98378815.53*	100	*99.86*
Fixed costs (FC)	**€/kg**	**€/yr.**	**% of total FC**	**% of TC**
Depreciation	0.08	8800	6.46	0.01
Rent	1.07	126000	92.57	0.13
Overheads	0.01	1320	0.97	0.00
Total	*1.16*	*136120*	100	*0.14*
External costs (EC)	**€/kg**	**€/yr.**	**% of total EC**	**% of TC**
Climate change	15.25	1788366.88	11.74	1.82
Ozone depletion	0.00531012	622.83	0.00	0.00
Terrestrial acidification	8.972585233	1052406.19	6.91	1.07
Freshwater eutrophication	0.580582727	68097.30	0.45	0.07
Marine eutrophication	0.496815831	58272.17	0.38	0.06
Human toxicity	19.79721698	2322041.32	15.24	2.36
Photochemical oxidant formation	0.895736318	105062.08	0.69	0.11
Particulate matter formation	19.00555798	2229186.60	14.63	2.26

Terrestrial ecotoxicity	14.81439537	1737599.69	11.40	1.76
Freshwater ecotoxicity	0.385755273	45245.74	0.30	0.05
Marine ecotoxicity	0.072345479	8485.50	0.06	0.01
Ionising radiation	7.754730951	909562.47	5.97	0.92
Agricultural land occupation	6.077319485	712816.70	4.68	0.72
Urban land occupation	35.7986057	4198865	27.56	4.26
Total	*129.90*	15236630.47	100	15.47
Total cost (TC)			**€/kg**	**€/yr.**
Sum of all costs			970	113751566

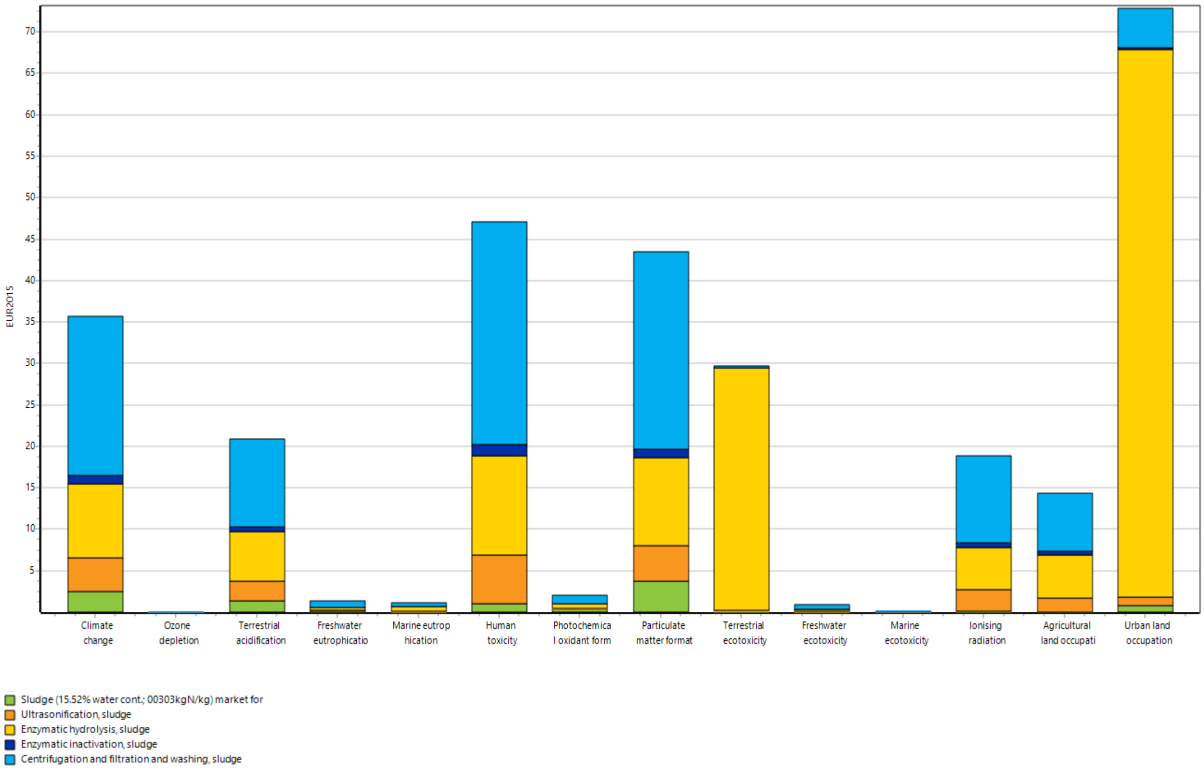

Figure 5. Weighted characterised impact results for the extraction of nitrogen from sludge from aquaculture. Calculated using the Environmental V.1 method.

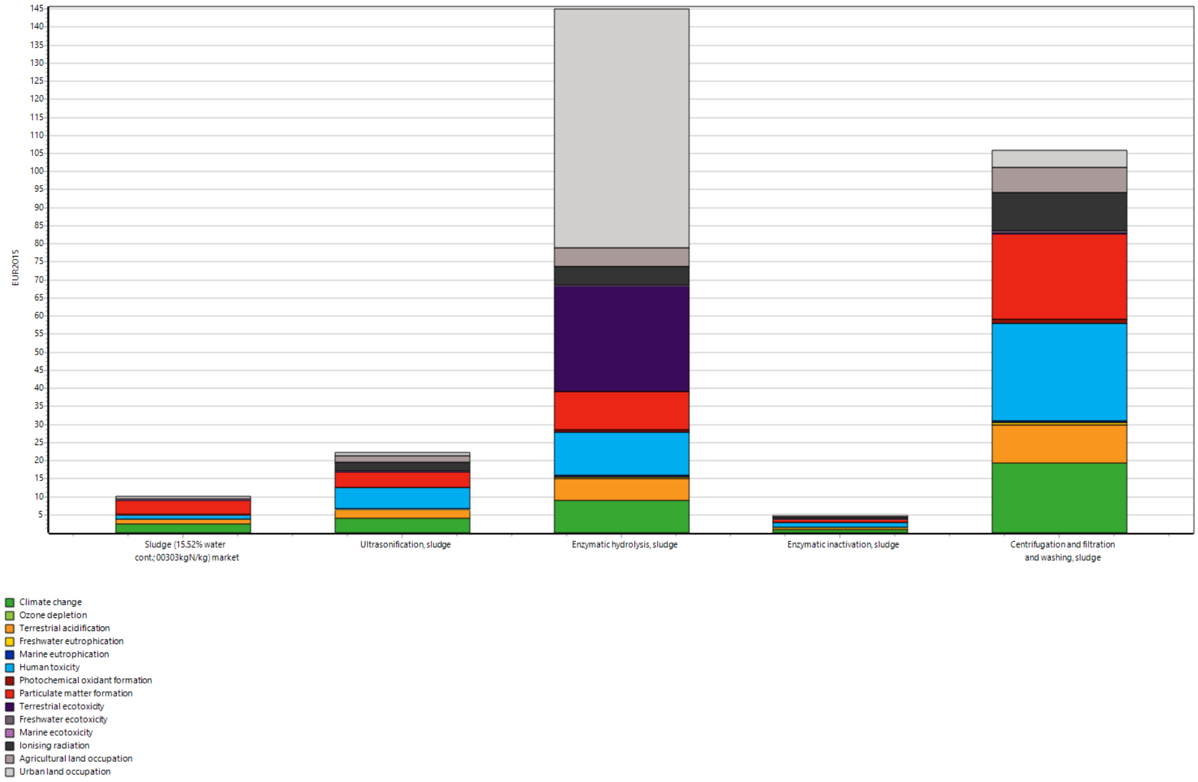

Figure 5. Aggregated Weighted characterised impact results for the extraction of nitrogen from sludge from aquaculture. Calculated using the Environmental V.1 method.

Table 7. Weighted characterised impact results for the extraction of nitrogen from sludge from aquaculture. Calculated using the Environmental V.1 method.

Impact category	Total	% of total				
		Sludge reception	**Ultrasonification**	**Enzymatic hydrolysis**	**Enzymatic inactivation**	**Centrifugation, filtration, and washing**
Total	288.467	3.504	7.745	50.273	1.771	36.708
Climate change	35.736	6.808	11.436	25.184	2.600	53.972
Ozone depletion	0.013	7.409	12.169	25.325	2.749	52.347
Terrestrial acidification	20.877	6.719	10.963	29.074	2.489	50.755
Freshwater eutrophication	1.399	0.470	13.209	26.812	2.997	56.513
Marine eutrophication	1.112	2.759	8.301	47.863	1.884	39.193
Human toxicity	47.110	2.195	12.420	25.480	2.821	57.084
Photochemical oxidant formation	2.038	15.291	9.455	23.244	2.151	49.859
Particulate matter formation	43.464	8.613	9.801	24.550	2.304	54.732
Terrestrial ecotoxicity	29.666	0.517	0.100	98.670	0.023	0.690
Freshwater ecotoxicity	0.877	1.534	9.393	22.552	2.143	64.378
Marine ecotoxicity	0.165	1.978	9.562	21.948	2.181	64.332
Ionising radiation	18.833	0.761	13.727	26.751	3.112	55.649
Agricultural land occupation	14.342	0.306	11.865	36.126	2.694	49.008
Urban land occupation	72.836	1.080	1.329	90.847	0.304	6.441

6 *Nannochloropsis* meal

Data describing OpEx and CapEx costs of producing dried *Nannochloropsis gaditana* dried meal were based mainly upon Vázquez-Romero et al. (2022), because this source refers to the system that features within the iFishIENCi project. The resulting total cost is 44 EUR per kg of dried meal (Table 8). Microalgae meal is usually marketed as a niche product and it frequently commands what may be considered as a high market price. The total cost of 44 EUR does seem somewhat high, but not excessively so, but it must be kept in mind that further improvements to the system efficiency are likely possible, resulting in reduced costs. Internalising negative environmental externalities increases the total costs to 79.27 EUR per kilogram of meal (Table 9).

Table 8. Budget statement for the production of *Nannochloropsis* dried meal.

OpEx	**€/kg**	**€/yr.**	**% of total OpEX**	**% of TC**
Consumables (nutrients, cleaning chemicals)	0.003	768861.03	0.01	0.01
Energy	0.01	1922152.56	0.03	0.01
Lighting	20.98	6185764180	98.88	47.22
Utilities	0.14	40553924.28	0.65	0.31
Wastewater treatment	0.002	705954.21	0.01	0.01
Others	0.08	23394344.12	0.37	0.18
Labour	0.01	2558210.32	0.04	0.02
Total	*21.217*	*6255667627*	*100*	*47.76*
CapEx	**€/kg**	**€/yr.**	**% of total CaPex**	**% of TC**
Detailed breakdown unavailable	23.21	6843259610	100	52.24
Total	*23.21*	*6843259610*	*100*	*52.24*
Total cost (TC)			**€/kg**	**€/yr.**
Sum of all costs			44	13098927237

Table 9. Budget statement for the extraction of nitrogen from aquaculture sludge, including the internalisation of environmental negative externalities.

OpEx	**€/kg**	**€/yr.**	**% of total VC**	**% of TC**
Consumables (nutrients, cleaning chemicals)	0.003	768861.03	0.01	0.01
Energy	0.01	1922152.56	0.03	0.01
Lighting	20.98	6185764180	98.88	47.22
Utilities	0.14	40553924.28	0.65	0.31
Wastewater treatment	0.002	705954.21	0.01	0.01
Others	0.08	23394344.12	0.37	0.18
Labour	0.01	2558210.32	0.04	0.02
Total	*21.217*	*6255667627*	*100*	*47.76*
CaPex	**€/kg**	**€/yr.**	**% of total CaPex**	**% of TC**
Detailed breakdown unavailable	23.21	6843259610	100	567583.22
Total	*23.21*	*6843259610*	*100*	*567583.22*
Externalised costs (EC)	**€/kg**	**€/yr.**	**% of total EC**	**% of TC**

Climate change	4.41	1301371314	12.67	5.57
Ozone depletion	0.0014	420079.0736	0.0041	0.0018
Terrestrial acidification	2.62	773323470.1	7.53	3.31
Freshwater eutrophication	0.16	46540116.44	0.45	0.20
Marine eutrophication	0.12	35201320	0.34	0.15
Human toxicity	6.31	1861203145	18.12	7.96
Photochemical oxidant formation	0.27	80499038.76	0.78	0.34
Particulate matter formation	5.97	1761626044	17.15	7.54
Terrestrial ecotoxicity	2.72	801284777.3	7.80	3.43
Freshwater ecotoxicity	0.26	75782687.63	0.74	0.32
Marine ecotoxicity	0.05	13914156.79	0.14	0.06
Ionising radiation	1.97	581882625	5.66	2.49
Agricultural land occupation	1.70	501682574.7	4.88	2.15
Urban land occupation	8.27	2437988658	23.73	10.43
Total	*34.84*	10272720007	100	43.95
Total costs (TC)			**€/kg**	**€/yr**
Sum of all costs			79.27	13098927271

Section 5 discussed the very high value of total costs per kg of nitrogen from sludge. However, the negative external environmental costs of *Nannochloropsis* dried meal are lower when nitrogen from sludge is used as a nutrient source than when the conventional nutrient source is used. Thus, if sufficient achievements through improved economies of scale and increased process synergy can be achieved for the extraction of nitrogen from sludge, this valorisation route for sludge may be financially feasible.

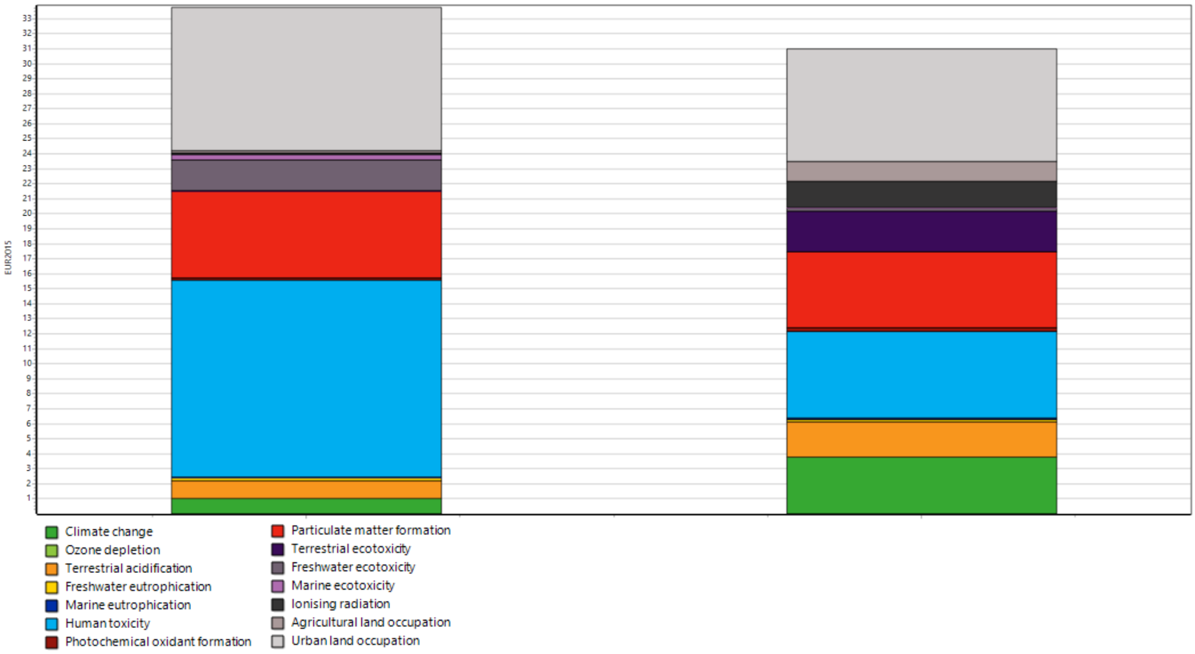

Figure 6. A comparison be the aggregated weighted characterised impact results of *Nannochloropsis* dried meal produced using a conventional nutrient supply (left bar) and of *Nannochloropsis* dried meal produced using nitrogen from aquaculture sludge (right bar). Calculated using the Environmental V.1 method.

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