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Life cycle assessment of fish feed for oil alternatives - environmental impact of microalgae, rapeseed and fish oil

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Abstract. Fish is an inexpensive source of high-quality protein as well as valuable micronutrients. Increasing the volume of fish and producing more fish feed is necessary to ensure the necessary consumption. One of the main components of fish feed is oil, the most crucial lipid source in fish feed. Fish oil is easily digestible and contains essential fatty acids, but replacing fish oil with alternative oil might make the fish feed more sustainable. Vegetable oils can replace fish oil due to reduced costs due to continued growth in production volumes, high availability and better economic value. Soy, linseed, rapeseed, sunflower, palm and olive oils are often used in fish feed. Also, microalgae oil is rich in essential fatty acids and a long-lasting alternative to fish oil. Important is not only the environmental impact of oil alternatives but also how these alternatives maintain or even improve the overall composition and quality of fish feed and products. An LCA assessment was performed to determine the environmental impact of microalgae, rapeseed oil, and fish oil. Where LCA system boundaries are "cradle to gate" and a functional unit of 1 kg of oil. LCA inventory is data from a literature review and SimaPro Ecoinvent database. The results obtained from LCA are based on PEFCR impact assessment categories. The LCA results show that the single score value for microalgae oil is 1.00E+00 mPt, for rapeseed oil 3.55E-01 mPt and fish oil 1.61E-01 mPt. It should be noted that the comparison presented reflects a generic comparison of alternatives, as the input data is derived from the literature analysis and the Ecoinvent v3.8 database.

Key words: fish feed; fish oil; LCA; microalgae oil; PEFCR; rapeseed oil.

INTRODUCTION

Over 2015-2020, total annual world aquaculture production grew by 3.3% per year (FAO, 2022). Aquaculture is one of the fastest-growing food production sectors, which can provide high-quality protein for human consumption, and there is a growing global demand for aquaculture products, but its development is raising concerns about its environmental impact (Adegboye et al., 2020; Kong et al., 2020).

With the expansion of aquaculture, the industry's criticism of environmental, economic and social sustainability has increased, and by focusing more on environmental sustainability, attention is focused on the impact of production systems on the environment and its better management to promote sustainability (Cao et al., 2013).

To improve sustainability in the choice of feed ingredients, it would be necessary to avoid the use of unsustainable feed ingredients such as meals, oils and silages/ hydrolysates derived from overexploited and/or unsustainably managed wild-caught marine fish, crustaceans, molluscs and aquatic species or from feed ingredient sources (Tacon et al., 2022).

Sustainable growth of aquaculture is possible by reducing dependence on fish oil for fish feed with fish oil alternatives which can provide the necessary fatty acids such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA) (Nasopoulou & Zabetakis, 2012; Cottrell et al., 2020; Zubair et al., 2021). The aquaculture sector uses plant-based raw materials to replace less sustainable raw materials in feed production (Zubair et al., 2021). However, replacing fish oil with a land plant alternative is more complex because land plants need to produce direct n-3 HUFA sources in sufficient quantities (Beal et al., 2018).

Vegetable oils often used in fish feed production are soybean, linseed, rapeseed, sunflower, palm and olive oils (Nasopoulou & Zabetakis, 2012). Rapeseed oil is a suitable lipid source for salmonids, freshwater and marine fish as it is rich in PUFA, especially linoleic acid (18:2 ω-6) and oleic acid (18:1 ω-9). Still, rapeseed oil does not contain n-3 PUFA (Nasopoulou & Zabetakis, 2012). Replacing fish oil with vegetable oil reduces costs, and vegetable oils have high availability and better economic value (Nasopoulou & Zabetakis, 2012).

Microalgae have a high lipid content, rich in essential long-chain polyunsaturated fatty acids (PUFAs), including omega-3 and omega-6 oils, and can replace fish oil in feed (Tacon et al., 2022). The advantages of microalgae oil include a fast growth rate, high antioxidant and colour content, and the availability of a wide range of species with a wide range of characteristics (Nagappan et al., 2021). Also, microalgae absorb CO_2 with CO_2 removal efficiency of 5% to 70% and thus produce O_2 during photosynthesis (Molino et al., 2019; Huang et al., 2021). Also, the cultivation of microalgae is beneficial for the prevention of global warming (Molino et al., 2020). However, the use of microalgae as lipids are limited by high production costs (Carvalho et al., 2022).

Fish oil is obtained from pelagic fish and is used in high-energy fish feed (Carvalho et al., 2022). To produce 1 kg of fish oil, there are needed 12.2 kg of fish (Naseem et al., 2021). Traditional aquaculture fish oil is popular and widely used, but it impacts the environment and reduces biological diversity (Carvalho et al., 2022).

At the suggestion of the European Commission, category rules for products were developed to have a uniform methodology for evaluating ecological parameters. Product Environmental Footprint Category Rules (PEFCR) Feed for food-producing animals aims to assess the ecological characteristics of compound feed in a coherent manner (European Commission, 2021). PEFCR defines more relevant impact categories - climate change, particulate matter, acidification terrestrial and freshwater, land use, eutrophication terrestrial, and water scarcity. However, in total, 18 Environmental Footprint impact categories are defined to be used to calculate the Product Environmental Footprint (PEF) profile.

Life Cycle Assessment (LCA) is used for PEF profile calculation based on PEFCR. LCA is an ISO-standardized methodology for environmental impact assessment from raw material acquisition to production, use and end-of-life treatment. Using the LCA method, different types of comparison can be made - comparison of product or raw material alternatives, the impact of energy or raw material alternatives of the effects of the product. The LCA study compared the environmental impact of two feed scenarios, one with a standard diet of fishmeal and oil and the other with vegetable protein and oil used in Atlantic salmon and rainbow trout farming. It concluded that the environmental burden is reduced by using plant alternatives (Boissy et al., 2011). A study on the LCA of Greater amberjack feed compared fish oil and a vegetable oil blend consisting of linseed oil, sunflower oil, and palm oil and concluded that replacing fish oil with vegetable oils would reduce wild fish use and greenhouse gas emissions. Still, there may be trade-offs, such as greater eutrophication to improve environmental sustainability in aquafeed production (Bordignon et al., 2023). LCA compares the environmental impact of fish oil production when different energy sources are compared and concludes that optimising production processes improves product quality and reduces environmental impact due to reduced energy consumption (Hilmarsdóttir et al., 2022).

Important aspects of the sustainability of fish feed are the availability of ingredients, their production method and transportation. This study compares oil alternatives used in fish feed production. According to the PEFCR methodology, fish oil, microalgae oil and rapeseed oil are compared to find out which of the alternatives has the least impact on the environment. The study also carried out a sensitivity analysis of the microalgae oil alternative with changes in the form of electricity.

MATERIALS AND METHODS

LCA consists of four stages - the goal and scope (defines the boundaries to be studied), inventory (accounting of relevant input/output data), impact assessment (evaluation based on assessment method), interpretation (conclusions and recommendations from the results) (International Organization for Standardization, 2006).

Goal and scope

The scope of the study includes the evaluation of oil alternatives used in fish feed production. The oil alternatives are microalgae oil, rapeseed oil and fish oil.

Functional Unit from PEFCR is 1 tonne of animal feed as fed. In this study function unit is 1 kg of oil because it corresponds to the collected data stream.

System boundaries

This LCA is ‘cradle to gate’ and system boundaries diagrams can be seen in Fig. 1 to Fig. 3 are for oil alternatives. Microalgae oil production data is from a literature review. Microalgae are obtained through a dark fermentation process, solid-liquid separation (Lu et al., 2021). Rapeseed oil and Fish oil production is from Ecoinvent v.3.8 database.

Life cycle stages

The product stage for all protein alternatives is divided into ‘Production of feed ingredients’, ‘Transport of feed ingredients to the feed mill’, and ‘Feed production’ modules. The components with the most significant impacts referring to the interpretation of results will be explained in this report as the relative effect of energy and raw materials in the life cycle stages.

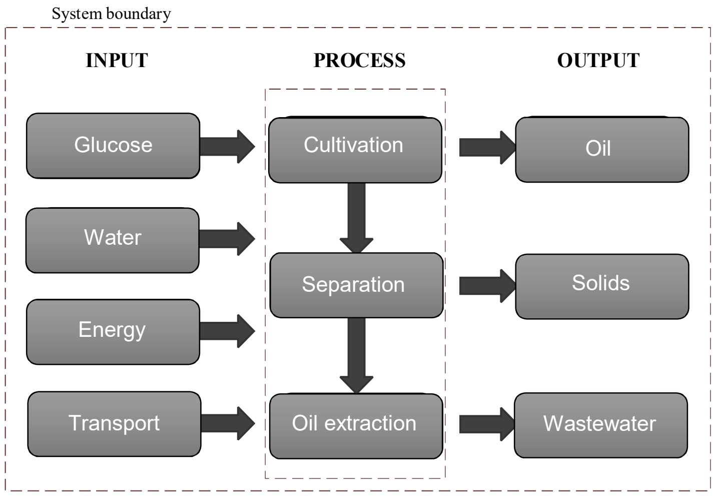

Figure 1. System boundaries for the cradle to gate for oil alternative – Microalgae oil (Lu et al., 2021).

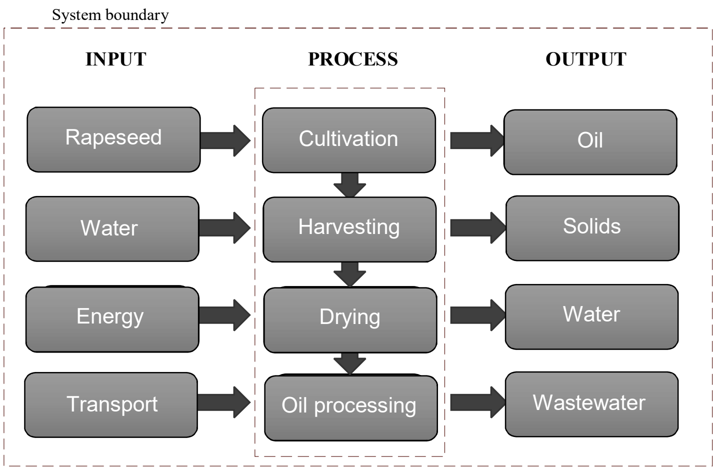

Figure 2. System boundaries for the cradle-to-gate for oil alternative – Rapeseed oil.

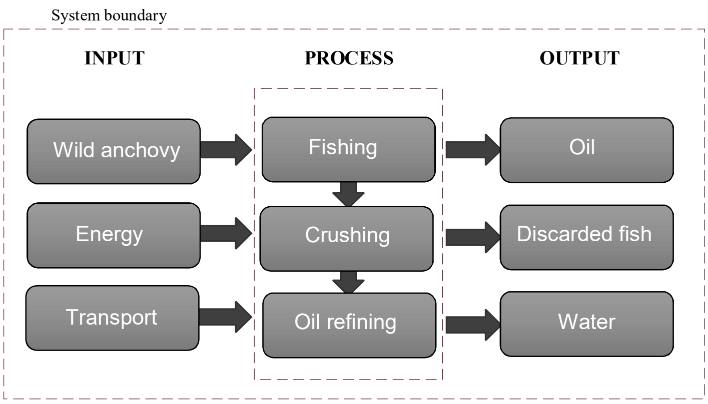

Figure 3. System boundaries for the cradle-to-gate for oil alternative – Fish oil.

Assumptions about relevant background data

Although the data are from the literature review and Ecoinvent v3.8 database, it is necessary to conduct an environmental impact assessment of the oil alternatives produced in the US. As much as possible used data in the LCA model is modified to the US. Inputs such as electricity and water are modelled for the US, but another type of energy is modelled based on global values. As much as possible, raw materials are for the US; if not, then use global or rest of the world data. Transport was also modelled for the US.

List of excluded processes

The necessary data have been collected from the literature and the Ecoinvent v3.8 database, and are few specific input data, and in this LCA model, the excluded process is the packaging.

Life Cycle Inventory Data

Table 1 to Table 3 shows inventory data for oil alternatives. Assumptions for Microalgae oil inventory are Sodium Glutamate is Sodium Nitrate, but corn syrup was less than 5% and was not included in the module.

Table 1. LCI for Microalgae oil (Lu et al., 2021)

Description	Amount	Unit
Input		
Glucose	3.2922	kg
Yeast	0.3687	kg
Sodium Nitrate	0.3687	kg
Potassium	0.0401	kg
Ammonium Sulfate	0.0184	kg
Magnesium	0.0121	kg
Iron	0.0001	kg
Enzymes	0.0651	kg
Tap water	4.4026	l
Electricity	3.0188	kWh
Output		
Water Evaporation	1.465	l
Algae Liquid	18.436	kg
Algae Flow	10.886	kg
Algae Waste Dry	0.880	kg
Water	2.190	kg
Products		
Microalgae oil	1	kg

Life Cycle Impact Assessment

The PEFCR Feed makes the impact assessment calculations for food-producing animals, where the necessary parameters are defined to characterise the environmental impact indicators.

Table 2. LCI for Rapeseed oil

Description	Amount	Unit
Input		kg
Rape seed	1.895	kg
Hexane	0.0004	kg
Electricity	0.111	kWh
Heat	0.227	MJ
Output		
Emissions	1.736	kg
Wastewater	0.00000087	m^3
Products		
Rapeseed oil	1	kg

Table 3. LCI for Fish oil

Description	Amount	Unit
Input		
Fish residues	6.309	kg
Cyclohexane	0.002	kg
Electricity	0.087	kWh
Heat	12.069	MJ
Output		
Emissions	0.602	kg
Products		
Fish oil	1	kg

The method used in SimaPro 9.4 software is EF 3.0, which incorporates the PEFCR as an impact assessment method. The impact categories are in the result section (Table 5).

RESULTS AND DISCUSSION

The Life cycle impact assessment calculations are made in full accordance with the Product environmental footprint category rules (PEFCR) Feed for food-producing animals, where the necessary parameters are defined to characterise the environmental impact indicators. This section presents the environmental performance results for all oil alternatives considering all input material flows.

Weighted results for all oil alternatives expressed in µPt value. Pt is the unit of the eco-indicator, and 1 Pt is representative of one thousand of the annual environmental load of an average European citizen.

In Fig. 4 are weighted results for impact categories, and in Table 4. Life cycle impact assessment results.

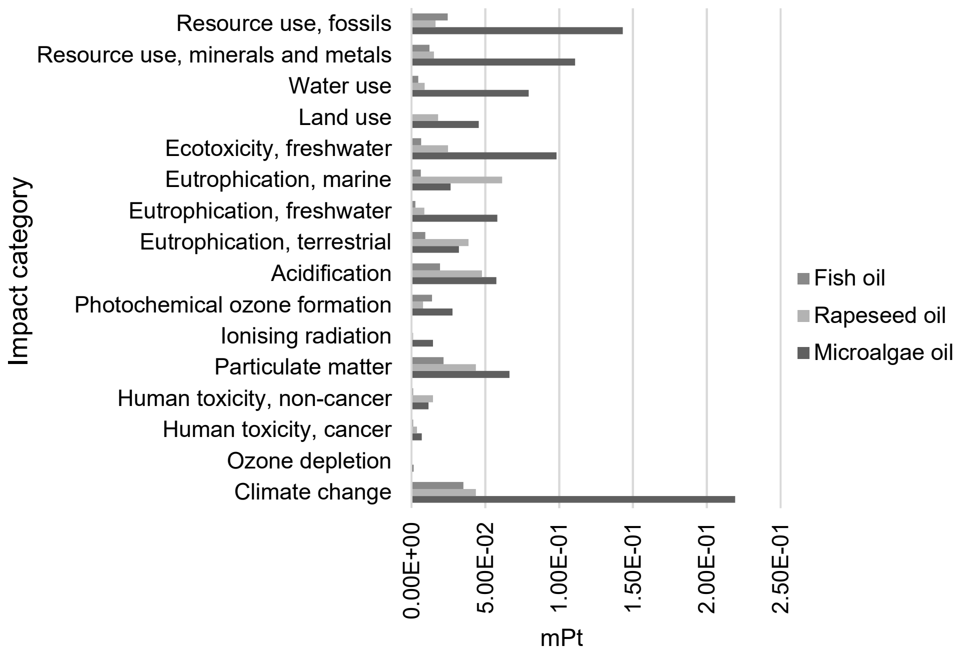

Figure 4. Oils weighted results for impact categories.

In this study, where FU 1 kg of oil according to PEFCR impact categories, fish oil has the least impact, followed by rapeseed oil and then microalgae oil. In a study with FU 1 ton of DHA, comparing the production of fish oil and algae oil expressed per 1 ton of DHA, the LCA results obtained by the ReCiPe 2016 method concluded that the algae alternative caused less ecosystem damage than the fish alternative, also in the sensitivity analysis (Bartek et al., 2021). In a study where EPA and DHA production from microalgae and fish biomass was compared according to CML 2001 methodology with LCA, where FU is 1 kg of EPA+DHA, it was concluded that microalgae oil alternative could replace fish oil (Bartek et al., 2021).

Table 4. Life cycle impact assessment results for oils

Impact category	Unit	Microalgae oil	Rapeseed oil	Fish oil
Climate change	kg $CO_{2\ eq}$	8.43E+00	1.68E+00	1.36E+00
Climate change - Biogenic	kg $CO_{2\ eq}$	3.52E-01	1.22E-03	1.14E-03
Climate change - Land use and LU change	kg $CO_{2\ eq}$	1.90E-01	2.16E-03	2.06E-03
Ozone depletion	kg CFC11 $_{eq}$	1.12E-06	1.93E-07	2.10E-07
Human toxicity, cancer	CTUh	5.56E-09	3.08E-09	8.98E-10
Human toxicity, non-cancer	CTUh	1.45E-07	1.83E-07	1.40E-08
Particulate matter	disease inc.	4.42E-07	2.91E-07	1.45E-07
Ionising radiation	kBq U^{235} $_{eq}$	1.23E+00	9.52E-02	6.27E-02
Photochemical ozone formation	kg NMVOC $_{eq}$	2.37E-02	6.67E-03	1.19E-02
Acidification	mol H+ $_{eq}$	5.16E-02	4.28E-02	1.75E-02
Eutrophication, terrestrial	mol N $_{eq}$	1.54E-01	1.84E-01	4.45E-02
Eutrophication, freshwater	kg P $_{eq}$	3.34E-03	5.11E-04	1.62E-04
Eutrophication, marine	kg N $_{eq}$	1.75E-02	4.07E-02	4.16E-03
Ecotoxicity, freshwater	CTUe	2.19E+02	5.50E+01	1.46E+01
Land use	Pt	4.71E+02	1.87E+02	4.05E+00
Water use	m^3 depriv.	1.07E+01	1.22E+00	6.21E-01
Resource use, minerals and metals	kg Sb $_{eq}$	9.35E-05	1.29E-05	1.03E-05
Resource use, fossils	MJ	1.12E+02	1.28E+01	1.93E+01

Sensitivity analysis

A sensitivity analysis is performed for the Microalgae oil alternative. In this sensitivity analysis, changes were made only to the electricity used - microalgae oil production used the US electricity and compared to production using Norwegian electricity. In Fig. 5 are the weighted results.

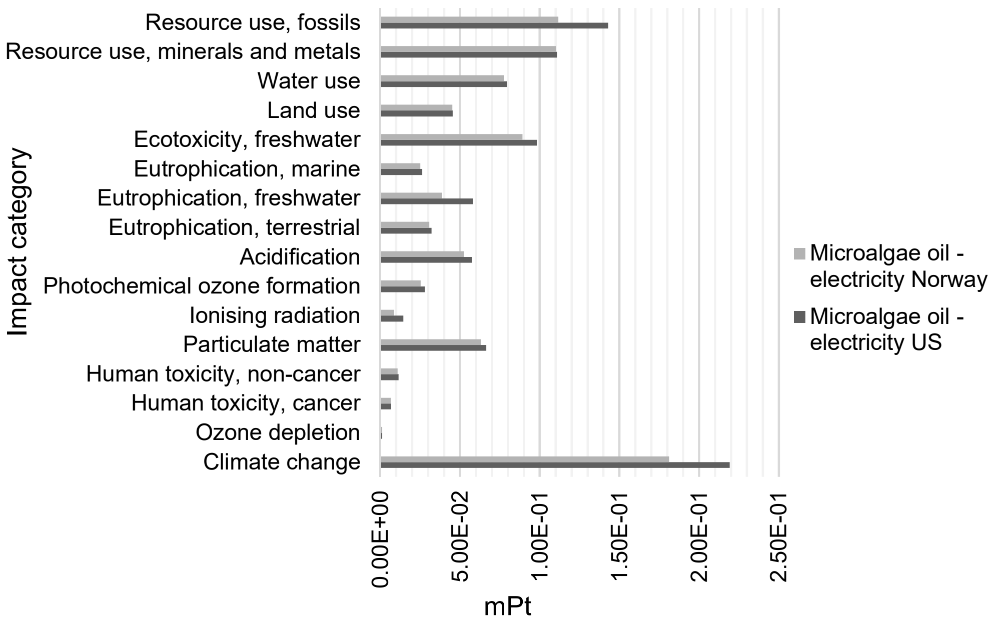

Figure 5. Microalgae oils sensitivity analysis weighted results for impact categories.

Table 5 shows results for Microalgae oil production in impact score per environmental category

Table 5. Characterisation results for Microalgae oil

Impact category	Unit	Electricity the US	Electricity Norway
Climate change	kg CO_2 $_{eq}$	8.43E+00	6.97E+00
Climate change - Biogenic	kg CO_2 $_{eq}$	3.52E-01	3.52E-01
Climate change - Land use and LU change	kg CO_2 $_{eq}$	1.90E-01	1.90E-01
Ozone depletion	kg CFC11 $_{eq}$	1.12E-06	1.04E-06
Human toxicity, cancer	CTUh	5.56E-09	5.27E-09
Human toxicity, non-cancer	CTUh	1.45E-07	1.37E-07
Particulate matter	disease inc.	4.42E-07	4.19E-07
Ionising radiation	kBq U^{235} $_{eq}$	1.23E+00	7.28E-01
Photochemical ozone formation	kg NMVOC $_{eq}$	2.37E-02	2.16E-02
Acidification	mol H+ $_{eq}$	5.16E-02	4.70E-02
Eutrophication, terrestrial	mol N $_{eq}$	1.54E-01	1.47E-01
Eutrophication, freshwater	kg P $_{eq}$	3.34E-03	2.23E-03
Eutrophication, marine	kg N $_{eq}$	1.75E-02	1.66E-02
Ecotoxicity, freshwater	CTUe	2.19E+02	1.99E+02
Land use	Pt	4.71E+02	4.67E+02
Water use	m^3 depriv.	1.07E+01	1.05E+01
Resource use, minerals and metals	kg Sb $_{eq}$	9.35E-05	9.29E-05
Resource use, fossils	MJ	1.12E+02	8.74E+01

CONCLUSIONS

An LCA study has been carried out for microalgae oil, rapeseed oil and fish oil. The document presents the results for the Functional Unit – 1 kg of oil. From PEFCR most relevant impact categories are Climate change, Particulate matter, Acidification, Land use, Eutrophication terrestrial and Water use.

Results for Microalgae oil for most relevant impact categories are Climate change - 8.43E+00 kg CO_2 eq, Particulate matter - 4.42E-07 disease inc., Acidification - 5.16E-02mol H+ eq, Land use - 4.71E+02 Pt, Eutrophication terrestrial - 1.54E-01 mol N eq, Water use - 1.07E+01 m^3 depriv.

Results for Rapeseed oil as most relevant impact categories are Climate change - 1.68E+00 kg CO_2 eq, Particulate matter - 2.91E-07 disease inc., Acidification - 4.28E-02 mol H+ eq, Land use - 1.87E+02 Pt, Eutrophication terrestrial - 1.84E-01 mol N eq, Water use - 1.22E+00 m^3 depriv.

Results for Fish oil as most relevant impact categories are Climate change - 1.36E+00 kg CO_2 eq, Particulate matter - 1.45E-07 disease inc., Acidification - 1.75E-02 mol H+ eq, Land use - 4.05E+00 Pt, Eutrophication terrestrial - 4.45E-02 mol N eq, Water use - 6.21E-01 m^3 depriv.

Sensitivity analysis was for Microalga oil alternatives - in one case, for production, it was used electricity in the US and in another case was used electracy in Norway. If production happens in Norway, the impact from used electricity is less impacting the environment than when production is in the US with the US electricity.

The total single score value for Microalga oil is 1.00E+00 mPt; the largest impact is from glucoses and electricity consumption. Impact can be reduced by using a greener electricity mix and more sustainable glucoses.

The total single score value for Rapeseed oil protein is 3.55E-01 mPt, and largest impact is from rape seed, and it is because of intensive or extensive cultivation processes. To reduce the impact can choose organically grown rape seed.

Total single score value for Fish oil is 1.61E-01 mPt and largest impact is from using fresh landed anchovy. To make a less impact it is possible to use more fish residues as main input for fish oil production.

Comparing the results of this study with other studies, it is concluded that the comparison of the impact on the environment is made according to different methodologies, but in the reviewed studies, the alternative of microalgae oil has a lower impact on the environment than the alternative of fish oil.

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