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Protein Alternatives for Use in Fish Feed – Life Cycle Assessment of Black Soldier Fly, Yellow Mealworm and Soybean Protein

Beate ZLAUGOTNE[1*], Fabian Andres Diaz Sanchez[2], Jelena PUBULE[3], Dagnija BLUMBERGA[4]

[1–4]*Institute of Energy Systems and Environment, Riga Technical University, Āzenes street 12/1, Riga, LV-1048, Latvia*

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Abstract – More production is needed as fish consumption increases. The increasing demand for fish also has implications for fish feed, the efficiency of its production and sustainability. Three protein alternatives – Black Soldier Fly, Yellow Mealworm, and Soybean – are compared to assess the sustainability of raw materials and their environmental impact. Each alternative has advantages and disadvantages. The advantages of Black Soldier fly and Yellow Mealworm are a valuable source of protein, sustainable growth (as the feed can be used in food waste) and no need for arable land. The disadvantages of Black Soldier fly and Yellow Mealworm are cost, unbalanced diets can adversely affect growth, and the nutritional impact on fish varies depending on the species of fly or mealworm. The advantages of soybeans are price, availability, and high protein content, while the disadvantages are the lack of essential amino acids, which affect the quality of the fish, and poor taste. An LCA study has been carried out on the proteins of black soldier fly, yellow mealworm and soybean. The most important impact categories from the PEFCR are climate change, particulate matter, acidification, land use, terrestrial eutrophication, and water use. The total single point value for the Black Soldier fly protein is 1.43E+01 µPt, the Yellow mealworm protein is 3.89E+02 µPt and the Soybean protein is 9.72E+01 µPt. The significant effect is due to the electricity consumption and the ingredients used in the feed. Sensitivity analysis was carried out for Black Soldier fly protein and Yellow Mealworm protein production where feed formulation was varied. In both sensitivity analyses, the lower environmental impact is from the new feed structure, which may be due to the use of food waste and wheat as feed ingredients in the new feed structure.

Keywords – Black soldier fly; fish feed; LCA; protein sustainability; soybean; yellow mealworm.

1. INTRODUCTION

It is expected that, under the influence of demand, fish production will increase almost three times by 2050 [1]. The consumption of fish in the human diet has increased, because fish contains valuable nutrients, such as polyunsaturated fatty acids with functional effects [2]. As population continues to grow and is creating the need for more food, and at the same time, the food needs to be sustainable to minimize environmental impact [3]. To provide the necessary quantities of fish, resource consumption increases, including fish feed.

* Corresponding author.
E-mail address: beate.zlaugotne@rtu.lv

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One way to reduce environmental impact is to choose more sustainable fish feed. Fish feed must be rich in protein and energy to meet fish's nutritional requirements [4]. One option is to choose a more sustainable source of protein, which makes up 18–50 % of the total fish diet [5]. Protein is an expensive and limiting ingredient used in feed [1]. A common source of protein has been fishmeal, but this is considered a risky option because as the price increases, the catch decreases. [6]. Also, over the past two decades, it has been recognized that fish meal resources are limited, and other alternatives are being chosen as a source of protein for fish feed [4].

Alternatives to fish meals should be widely available, have good nutritional qualities, like a low carbohydrate and anti-nutritional factors, high protein content, adequate amino acid profile, high digestibility, and palatability, and, importantly, be a competitively priced alternative [7]. The nutritional requirements of fish vary from species to species, which should also be considered when assessing fish feed [8]. Options should also ensure positive effects on fish, such as feed conversion ratio, specific growth rate, final weight, and survival of different fish species [9].

Insect meal is considered a sustainable source of protein because it uses by-products, does not require agricultural land to grow insects, uses little water, and there is an opportunity to reduce greenhouse gas emissions if food waste is used as feed [10]. Black Soldier Fly larvae can also use food waste as food and then this food waste is converted into high-quality Black Soldier Fly protein [11]. Balanced amino acid profile similar to fish meal and better than it is for soybean protein [12]. Yellow Mealworm is a good alternative because of its high protein content, balanced amino acid profile, efficient feed conversion in cultivation and ability to live from organic by-products, low greenhouse gas emissions and water footprint, and reduced land use and possible mass production [13].

One of the alternatives to a fish meal is the use of plant proteins because it is more environmentally friendly and economically beneficial, and soybean protein is one of the most accessible and economically beneficial plant proteins with a high protein content, constant composition, and a good amino acid profile [14]. Fish feed with soybean meal is easily digestible because it contains crude protein [15]. The European Commission has developed a uniform environmental impact assessment Black Soldier Fly larvae can convert food waste into high-quality protein guidelines and obtain comparable economic characteristics for product categories – Product Environmental Footprint Category Rules (PEFCR) Feed for food-producing animals [16]. Ecological characteristics are expressed in 18 environmental impact categories and parameters. From PEFCR most relevant categories are climate change, particulate matter, acidification terrestrial and freshwater, land use, eutrophication terrestrial, and water scarcity.

The Life Cycle Assessment (LCA) is one of the tools that can be used for environmental impact assessment following the PEFCR guidelines. The LCA methodology evaluates environmental impacts throughout the life cycle of a product or service with a standardized approach. LCA is widely used in various sectors to evaluate products or services, raw materials, transport, and end-of-life scenarios. Also, sensitivity analysis can be performed for products or services by changing one or more parameters. The study used LCA, an observation is made on the protein source of fish meal, soybean meal and rapeseed meal used in trout fish feed, and it is concluded that fish meal has a more significant impact on the environment than the plant protein alternative [17]. The other LCA study compared partial algae and insect-based diets with a conventional fish meal and fish oil diet for salmon. It concluded that the alternative algae and insect-based diet had a more significant environmental impact than the fish meal and fish oil diet [18]. As well as in another study LCA evaluates protein extraction from mealworms fed on cereal or plant food waste, and by-

products and protein extraction from black soldier fly larvae fed on brewery by-products and plant waste, and the study concluded that using insects in the diet vegetables with low economic value may compete environmentally with existing protein sources in fish feed [19]. Studies have also been conducted on the effects of other fish feed ingredients, as pigment [20] and oil [21].

Aim of the research is to perform an environmental impact assessment using attributional LCA for three-protein alternatives and comparing insect and plant protein alternatives – Black Soldier Fly, Yellow Mealworm, and Soybean protein. Results will be expressed based on PEFCR categories, and sensitivity analysis will be performed for Black Soldier Fly and Yellow Mealworm protein alternatives using different insect diet composition.

2. METHODS

LCA is performed according to ISO 14040 Environmental management – Life cycle assessment – Principles and framework standard [22] and ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines [23]. Four main phases in LCA – definition of the goal and scope, inventory, impact assessment and interpretation of results. *SimaPro 9.4* software was used for assessment.

2.1. Goal and Scope

Goal is to assess an environmental impact assessment for Black Soldier Fly, Yellow Mealworm and Soybean protein.

Scope is procurement and transportation of raw materials and production processes can characterize the Functional Unit and PEFCR functional unit is 1 ton of animal feed. However, the functional unit used in this study is 1 kg of protein because it is consistent with the collected data flow.

2.2. System Boundary

To be able to compare different alternatives, it is defined that this LCA accounts for the life cycle of the product as “from the cradle to the gate”, where the assessment is from resource extraction to the factory gate. System boundaries can be seen in Figs. 1–3 for protein alternatives. Black Solder fly and Yellow Mealworm protein production data are from a literature review, and Soybean protein production is from *Ecoinvent v.3.8* databases.

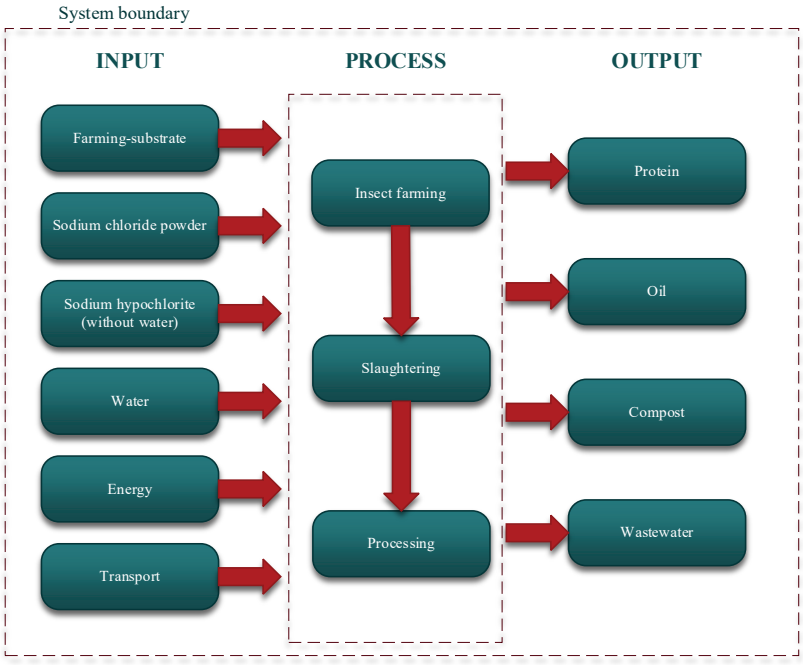


Fig. 1. System boundaries for the cradle-to-gate for protein alternative – Black Solder fly protein [8].

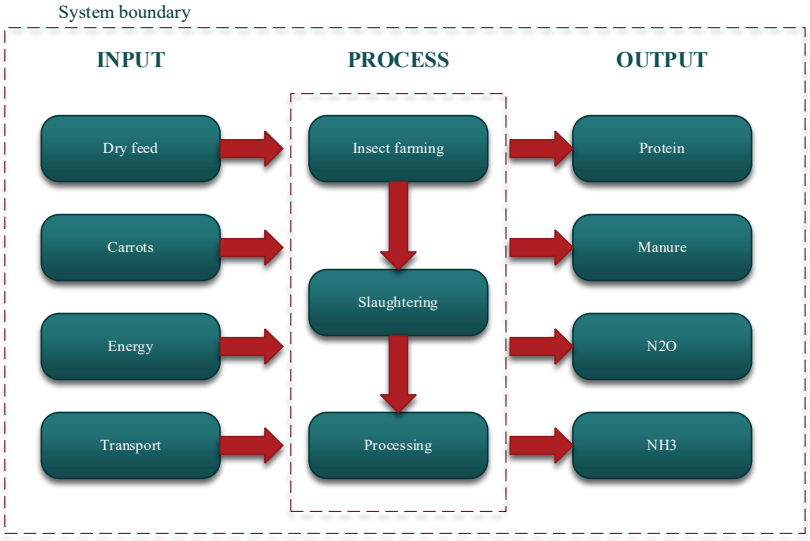


Fig. 2. System boundaries for the cradle-to-gate for protein alternative – Yellow Mealworm protein [24].

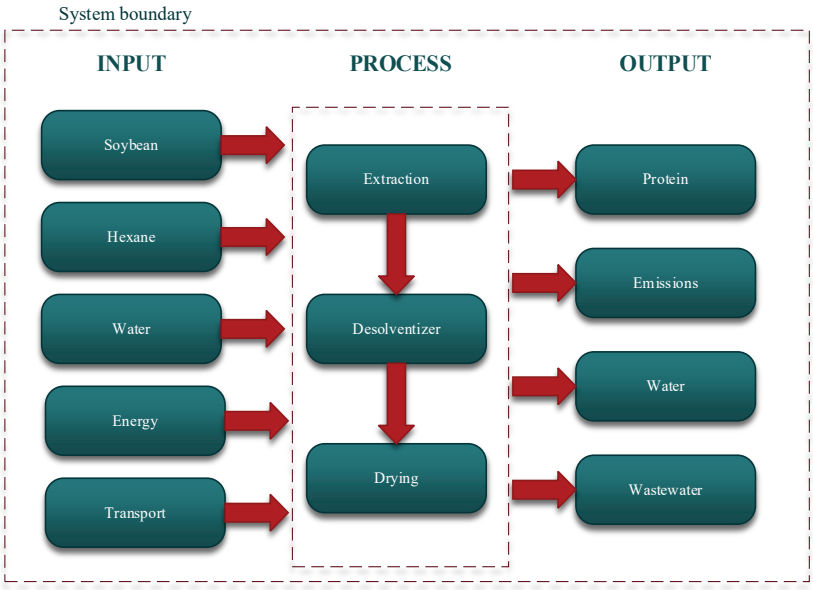


Fig. 3. System boundaries for the cradle-to-gate for protein alternative – Soybean protein.

2.3. Life Cycle Stages

Production of feed ingredients, transport of feed ingredients to the feed mill, and feed production modules are product stages. The LCA inventory section has a complete list of raw materials to produce one functional unit for all products. For Black Solder fly protein and Yellow Mealworm protein, input data is from literature, but for soybean protein, input data is from the *Ecoinvent* database.

Although the data is from the literature review and the *Ecoinvent v3.8* database, assumptions have been made about the relevant background data. An assumption was made that the protein is produced in Norway, and the input data were modified to a Norwegian (electricity and water) or European (heat and transport) scale and raw materials as far as possible in Norway or Europe. But there are also input data that are global or worldwide. In this case, the excluded process is the packaging. Production equipment and technical lifespan have not been considered, because no data of this type is available.

2.4. Life Cycle Inventory Analysis

Table 1 to Table 3 are inventory data for protein alternatives to produce 1 kg of protein. Modeling according to inventory data, some of the input data in the model are created differently, as farming-substrate was modeled as compost and dry feed consisted of wheat bran, bread, brewer's yeast and lucerne. Allocation is only for the main product – protein because among the selected alternatives, the output data is not completely specified.

TABLE 1. LCI FOR BLACK SOLDER FLY PROTEIN [8]

Description	Amount	Unit
Input		
Farming-substrate	6	kg
Sodium chloride powder	0.0017	kg
Sodium hypochlorite (without water)	0.0017	kg
Water consumption	6.3	kg
Energy consumption	3.367	kWh
Output		
Oil	0.333	kg
Field application as compost	8.017	kg
Wastewater discharge in the drainage system	0.003	m^3
Products		
Black Solder fly protein	1	kg

TABLE 2. LCI FOR YELLOW MEALWORM PROTEIN [24]

Description	Amount	Unit
Input		kg
Dry feed	3.61	kg
Carrots	2.78	kg
Electricity consumption	12.34	MJ
Output		
N_2O (animal-related)	25.50	mg
NH_3 (animal-related)	< 1	mg
Manure	2.18	kg
Products		
Yellow Mealworm protein	1	kg

TABLE 3. LCI FOR SOYBEAN PROTEIN [DATA FROM *ECOINVENT V3.8* DATABASE]

Description	Amount	Unit
Input		
Hexane	0.00036	kg
Soybean	0.90759	kg
Water	0.46028	kg
Electricity	0.04181	MJ
Heat	0.54350	MJ
Output		
Hexane	0.00036	kg
Hydrogen chloride	0.00005	kg
Water	0.00011	m^3
Products		
Soybean protein	1	kg

2.5. Life Cycle Impact Assessment

PEFCR Feed for food-producing animals describes impact assessment categories and using *SimaPro 9.4* software used method EF 3.0, which corresponds to PEFCR. The impact score is derived from 16 categories that are expressed in µPt value. Pt is the unit of the eco-indicator, and 1 Pt is representative of one thousand of the annual environmental loads of an average European citizen.

3. RESULTS

Results from LCA are expressed based on PEFCR impact assessment categories. In Fig. 4 are weighted results for impact categories based on PEFCR. The biggest impact occurs in the for all protein alternatives is climate change and for Yellow mealworm protein and Soybean protein is eutrophication freshwater and eutrophication marine, but for Black solder fly protein resource use minerals and metals and resource use fossils categories. In this case Black solder fly protein has the least impact on ozone depletion, eutrophication, and marine and land use categories. Based on this research, Yellow mealworm protein has minor effects on ozone depletion, human toxicity cancer and ionizing radiation. But ozone depletion, ionizing radiation and water use are categories which have a small effect on Soybean protein in this case.

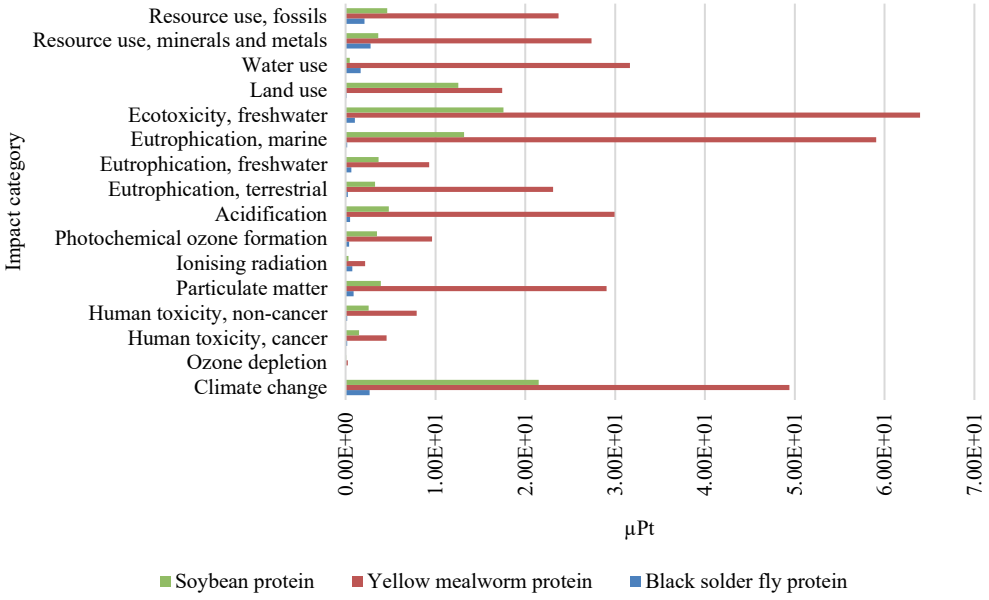


Fig. 4. Weighted protein results for impact categories.

Results from this study show that the least impact on the environment is from Black Solder fly, followed by Yellow Mealworm protein alternative. The LCA study comparing protein from two types of insect meal results show that based on climate change results in Black soldier fly has the lowest impact in comparison with Mealworm [19].

3.1. Sensitivity Analysis

A sensitivity analysis is performed to find out how the impact on the environment changes if one of the components is replaced. After the sensitivity analysis, it can be concluded whether the selected variable component causes a large change in the impact of the product on the environment. A sensitivity analysis is performed for Black Solder fly protein and Yellow Mealworm protein alternative. In this sensitivity analysis, changes were made only to the feed composition in Fig. 5 and Fig. 6. Components were changed to see their overall effect on the final product – protein. It was chosen to compare feed for both insect alternatives because it is a factor that accounts for part of the value of the total environmental impact of the product. The existing feed composition is from a literature review, which was compared with insect feed used in production. In the composition of feed, input data such as compost, food loss from dairy and bakery, brewer's yeast and spent grains were modeled without influence, as they are generated or are as leftovers from other product production.

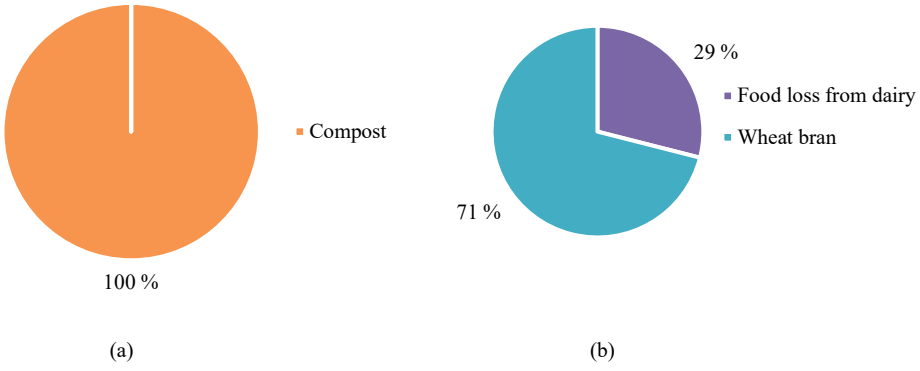


Fig. 5. Black Solder fly feed component. a) Original feed component; b) New feed component.

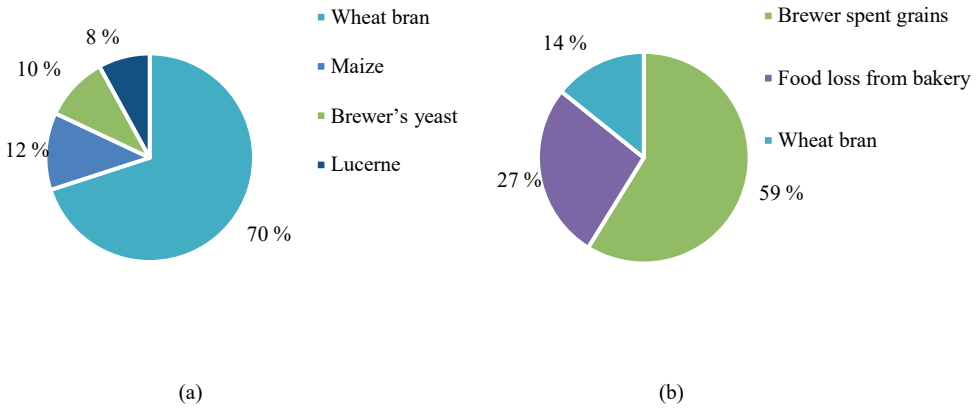


Fig. 6. Yellow Mealworm feed component. a) Original feed component; b) New feed component.

Fig. 7 shows weighted results for impact categories. In this sensitivity analysis, the biggest impact is from ecotoxicity freshwater, eutrophication marine and climate change categories. The new feed structure will increase the Black Solder fly protein impact by 96 %.

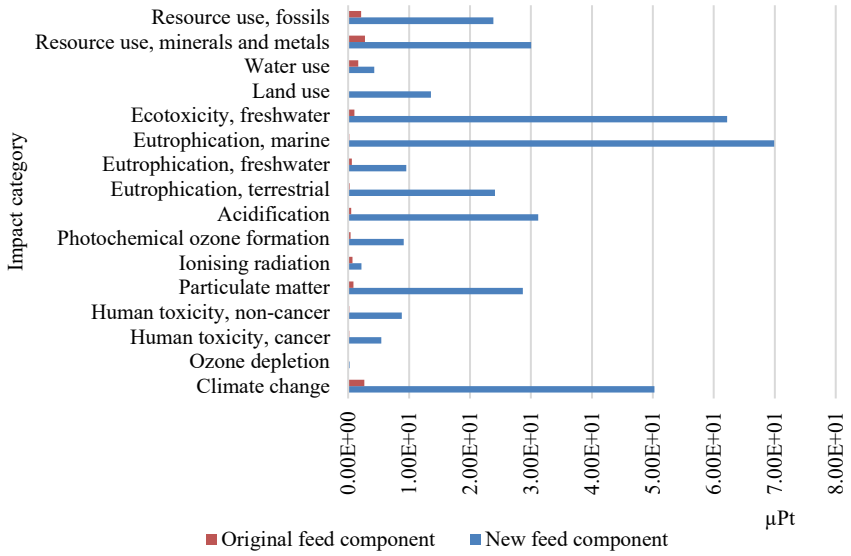


Fig. 7. Black Solder fly weighted protein results for impact categories for both feed structure.

Fig. 8 shows weighted results for impact categories. Ecotoxicity freshwater, eutrophication marine and climate change categories make a larger impact in this sensitivity analysis. The new feed structure increases the impact of total Yellow Mealworm protein by 40 %.

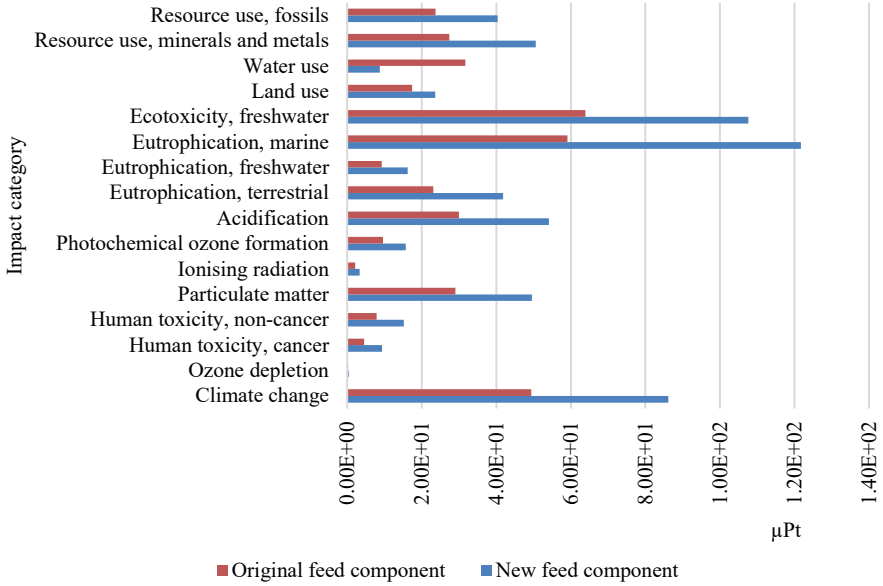


Fig. 8. Yellow Mealworm protein weighted results for impact categories for both feed structure.

4. CONCLUSION

An LCA study has been carried out for the Black Solder fly, Yellow Mealworm and Soybean protein. The LCA study used data from the literature and the *Ecoinvent* database. The document presents the results for the Functional Unit – 1 kg of protein. For a more accurate product comparison, the functional unit can be the protein concentration, but no data were found about protein concentration in the literature review. From PEFCR most relevant impact categories are Climate change, Particulate matter, Acidification, Land use, Eutrophication terrestrial and Water use. Of course, the (marine) biodiversity impact category can also be determined with additional methods, but the results of this LCA study are according to PEFCR.

Black Solder fly protein results for most relevant impact categories are Climate change 1.02E–01 kg CO_2eq, Particulate matter 5.87E–09 disease inc., Acidification 4.43E–04 mol H^+eq, Land use 1.21E+00 Pt, Eutrophication terrestrial 1.16E–03 mol Neq, Water use 2.26E–01 m^3 depriv. The total single score value for Black Solder fly protein is 1.43E+01 µPt, and the most significant impact is from electricity consumption. To reduce the impact on the environment, a greener electricity mix can be chosen or review the equipment used in production processes and their efficiency.

Results for Yellow Mealworm protein as most relevant impact categories are Climate change 1.70E+00 kg CO_2eq, Particulate matter 1.72E–07 disease inc., Acidification 2.40E–02 mol H+eq, Land use 1.61E+02 Pt, Eutrophication terrestrial 9.82E–02 mol Neq, Water use 3.81E+00 m^3 depriv. The total single score value for Yellow Mealworm protein is 3.89E+02 µPt, and the most significant impact is from mealworm feed ingredient – wheat. Reducing the impact on the environment might be necessary to replace the components in mealworm feed, as a sensitivity analysis can show that ratio changes in feed make a less environmental impact than the initially used ratio from literature.

Results for Soybean protein as most relevant impact categories are Climate change 8.26E–01 kg CO_2eq, Particulate matter 2.61E–08 disease inc., Acidification 4.33E–03 mol H+eq, Land use 1.29E+02 Pt, Eutrophication terrestrial 1.57E–02 mol Neq, Water use 6.01E–02 m^3 depriv. The total single score value for Soybean protein is 9.72E+01 µPt, and the most significant impact is from manure that used to grow soybeans. To reduce environmental impact, need to look at fertilizer alternatives and choose the one with the lowest impact. Also, improve and make a more sustainable soybean growing phase.

Sensitivity analysis was performed for Black Solder fly protein and Yellow Mealworm protein production, where feed composition was changed. The total single score for Black Solder fly protein original feed component is 1.43E+01 µPt, and for the new feed component 3.75E+02 µPt in this case, less environmental impact is from the original insect feed structure. The total single score for Yellow Mealworm protein original feed component is 3.47E+02 µPt, and for the new feed component 5.76E+02 µPt and less environmental impact is from the original insect feed structure. In both sensitivity analysis cases, the new feed structure uses food loss and wheat materials but has the largest impact to environment.

The results obtained in this study agree with the previously reviewed literature, as a source of protein is being sought to be used in fish feed with the least possible impact on the environment, and considering insects as an alternative, insect feed is very important. What can also be concluded after the sensitivity analysis carried out in the study, when choosing insect food, this alternative can have a greater impact.

Each alternative has advantages and disadvantages. The advantages for Black Solder fly and Yellow Mealworm are a valuable source of protein, sustainable growth (as feed can be used for food waste) and no need for arable land. Disadvantages for Black Solder fly and

Yellow Mealworm are price, an unbalanced diet can negatively affect growth, and nutritional value effect on the fish vary depending on fly or mealworm species. The advantages of soybeans are price, availability, and high protein content, but the disadvantages are a lack of essential amino acids that affect the quality of fish and poor palatability.

The study used LCA, an observation is made on the protein source of fish meal, soybean meal and rapeseed meal used in trout fish feed, and it is concluded that fish meal has a more significant impact on the environment than the plant protein alternative [17]. The other LCA study compared partial algae and insect-based diets with a conventional fish meal and fish oil diet for salmon. It concluded that the alternative algae and insect-based diet had a more significant environmental impact than the fish meal and fish oil diet [18]. As well as in another study LCA evaluates protein extraction from mealworms fed on cereal or plant food waste, and by-products and protein extraction from black soldier fly larvae fed on brewery by-products and plant waste, and the study concluded that using insects in the diet vegetables with low economic value may compete environmentally with existing protein sources in fish feed [19].

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