Case Study

# Environmental performance of insect protein: a case of LCA results for fish feed produced in Norway

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## Abstract

In this article, life cycle assessments for six insect protein production cases are examined, and their life cycle inventories are systematically combined to create consistent data and results for the environmental performance of insect protein. The LCAs are on mealworms farmed in the Netherlands or France, fed on cereals or vegetable waste food and brewery side stream (four cases); and black soldier fly larvae farmed in Germany, fed on brewery side stream or brewery side stream with vegetable waste (two cases). The focus is on those insect proteins which can be utilised as fish feed with use in Norway as an example. Special attention is paid to obtain consistent system boundaries, method choices, background data, and indicators. The results show that the insect diet is crucial for all the analysed environmental indicators for insects fed a diet of high economic value vegetables. Emissions from the utilisation of insect manure for biogas, fertilisers or similar, and direct insect greenhouse gas emissions, seem to have little importance. The article further shows results compared with the greenhouse gas emissions for the most important salmon protein feed ingredients in Norway. Insect protein based on vegetables with low economic value has the potential to compete in environmental performance with existing protein sources for fish feed and can also cover 10 to 15% of the volumes of crude protein currently imported to the EU.

## Article highlights

- Protein from insects fed on 'waste' (as is most often the case), have a climate change burden which is equal to or much lower than the most common crop-based fish feed protein ingredients.
- Proteins from insects can provide 10–15% of the crude protein imported to the EU.
- Transport of insect protein from countries such as The Netherlands, France and Germany to the west coast of Norway makes only a marginal contribution to the environmental burdens.

**Keywords** Protein · Insects · Feed · Life cycle assessment · Product environmental footprint · Reproducibility

## 1 Introduction

The human consumption of protein in EU countries is currently 50% higher than that stipulated in the dietary requirements set by the World Health Organization (WHO) [1]. Nevertheless, there is a current shortage of protein in Europe for use in animal feed. Significant amounts of protein, soy in particular [2], are therefore being imported. As there are restrictions on the utilisation of fish meal from wild caught fish, this shortfall with regard to fish feed will most probably increase over the coming years. There is an ongoing quest within the EU for protein sources that are

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both environmentally friendly and economically realistic [2, 3]. As supplies from outside Europe are affected by climate breakdown and the challenges associated with land use change in the production of soy, the aim is to extend the EU's self-sufficiency in protein [3, 4].

Several initiatives, both worldwide [5] and within Europe [6] are being launched to explore new protein sources. The quest for alternative protein sources is not a recent endeavour, and examples from the 1970s are to be found, stating that "practically no potential feed material has been ignored" [7]. Proteins for animal or human consumption may come from plant sources, animal sources or industrial manufacturing, and feed producers base their choice of protein sources on a range of variables. These include price, availability, the amino acid profile, and, to an increasing extent, the environmental impact. Protein from insects could become an alternative for feed producers, while at the same time fulfilling the EU requirements for additional protein sources and reducing the climate burden.

Although there is scant reporting to be found in literature on the environmental performance of insect production, van Huis and Oonincx [8] refer to studies showing that fishmeal can be replaced with insect meal. The degree of substitution and insect larvae types vary across fish species. The efficiency of insects in the conversion of organic matter into animal protein and dietary energy, is high in comparison with traditional husbandry [9] and their potential within future food systems is significant, offering an environmentally friendly option both as food and feed [10]. The same authors [8] also showed that in addition to a reduction in greenhouse gas emissions, the principal environmental advantages of insect farming over the production of livestock are to be found in the employment of land and water resources. An Austrian study [11] showed that protein for human consumption from mealworm, compared with broilers (also for human consumption), was more environmentally beneficial for four out of five examined indicators.

Previous studies on the environmental performance of insect meal production underline the significant stages of the insect life cycle, these being insect diet [9, 11] and energy use during rearing [8, 11]. Some also refer to these factors indirectly via the cost of insect diet [6] and processing [10], in addition to direct insect greenhouse gas emissions [8]; processing and storage [8]; buildings and other infrastructure [8, 12], and waste handling [8, 13, 14].

Insect diet is a major contributor to environmental indicators. This burden can be reduced by replacing the diet with by-products or waste substrates. These must be of sufficient quality to positively influence larvae yield, body weight, and the nutrient composition of black soldier fly larvae [15]. Diet variations of different insect species should be taken into consideration; while some larvae are best suited to a diet consisting of meat waste [10], house fly larvae grow well in the manure of animals with a mixed diet, although not in the manure of herbivores such as cows, goats and horses. Black soldier fly larvae were found to accept a wider variety of decaying organic matter. Oonincx, van Broekhoven [16] provided two examples, the first showing that a mealworm diet with carrots increased dry matter level and N-efficiency, while decreasing growth time. The second showed that the addition of beer yeast to high protein diets could lead to a shorter growth time and a higher survival rate. Studies on nutritional issues have revealed that by-products and waste substrates can satisfactorily fill the requirements of rearing insect larvae [12, 13].

One study shows that the amount of energy required to regulate temperature can be influenced by geographical location, as temperatures below a certain level can have a negative effect on the growth and even survival of the insects [9]. The authors of this study also found that the types and quantities of construction materials in buildings where insects were farmed were more likely to be selected for their availability and in relation to the requirements of climate, than to meet the needs of a specific farmed animal. Roffeis et al. [14] carried out the only study that mentions the effect on environmental impacts of construction choices, specifically with regard to infrastructure and building materials. They established that the aforementioned impacts are 'largely explained by fundamental biophysical inputs, such as energy, water, milk powder and sugar…'.

Most of the studies reported are based on Life Cycle Assessment (LCA), which provides a framework for systemic analysis of the impact of products and services on a range of environmental issues [17]. This ensures that no important life cycle stages are omitted from the study and that the focus is on more than just one type of potential environmental impact. Although LCA has a uniform methodological framework, differing method choices, assumptions, and databases employed across studies can create variations in results for similar products. For this reason it can be difficult to make comparisons with previous studies on insect protein.

This study aims therefore to transform existing knowledge into consistent LCAs, and thus enable the comparison of insect proteins, both between different insect proteins and with other proteins already in use for fish feed today. This will assist stakeholders in selecting optimal solutions. There is little documentation in literature of the environmental profile of insect proteins for fish feed and there is a need for the performance of further LCAs. If the environmental profile from such LCAs corresponds with the environmental performance hitherto reported in literature, insect proteins could fulfil several EU requirements.

These could include an increase in protein self-sufficiency and a reduction both in climate emissions and in pressure on land use. Together the utilisation of insect proteins and the application of LCA could make a significant contribution to a global reduction in GHG.

Norway was selected as the final destination for the insect protein, as it is by far the largest producer of farmed fish in the EU, with salmon being the number one farmed animal.

In the next section, the methodological choices and assumptions are explained. Chapter 3 presents the results of the study, comparing reproduced and original results; showing results for different environmental impacts for the constructed cases; and comparing insect proteins with other protein sources. In chapter 4 the results are discussed in more detail while conclusions are given in chapter 5.

## 2 Methods

The method underlying the article is LCA, where a study of insect protein and other protein sources is based on the assembly and streamlining of previous studies. This method section explains the way in which data from previous studies have been assembled to create comparative cases.

### 2.1 Goal and scope of the LCA

The aim of this study has been to transform existing knowledge on insect proteins into LCAs, to facilitate a comparison with more conventional protein sources. There has been a focus on those insect proteins which could be utilised as fish feed. To enable the performance of LCAs, a three-step procedure has been carried out:

- Reproduction of studies found in literature;
- Comparison of reproduced results with the original results; and
- Construction of cases by combining inventories from literature

Firstly, a reproduction of results from previously published and peer-reviewed studies was made, to enable a decision as to whether the inventories were suitable for use in further studies. This was achieved by comparing the reproduced results with those from the original studies (second step). As a third step, a number of cases were constructed by combining inventories, enabling consistent LCAs to be performed with regard to system boundaries, background data, and indicators. Lastly, the results have been compared with the greenhouse gas emissions for the most important salmon feed ingredients in Norway in 2017. In addition, the production potential of insects has been calculated and compared with the protein deficit for Europe.

### 2.2 Type of LCA

The study is based on so-called attributional LCA methodology [17] with the aim of accounting the environmental performance of the protein sources. The primary methodology used has been LCA in accordance with ISO 14040 [18] and ISO 14044 [19].

### 2.3 Functional unit

The functional unit for the constructed cases in this study is 1 kg of protein from insect meal delivered to the west coast of Norway. This functional unit includes an adjustment for the amount of protein in the insect meal. If the crude protein content is low, more meal is required to deliver 1 kg of protein, with a subsequent increase in the transport burden from the place of origin to the chosen location.

### 2.4 System boundaries

The modelling of the constructed insect protein value chains has included all upstream processes through to the delivered protein at the fish farm, close to where the fish feed production is assumed to take place (cradle to gate). Although it is only the insect meal itself that is considered in this study, the insect meal is assumed to be mixed with other ingredients before being used as fish feed.

In the given cases, production of the insect diet, insect farming and the processing of insect meal are all located in the Netherlands, France and Germany (see details in Table 1). The insect meal is then transported to the west coast of Norway. Figure 1 shows the included processes and the actual system boundaries for the constructed cases.

The peer-reviewed studies employed as the basis for the modelling were published in the period 2011 to 2018. The most significant background processes taken from databases are from the periods 1996–2002 and 2009–2016.

### 2.5 Data sources/life cycle inventory

The environmental performance of insect production is not widely reported in literature, and only one dataset was found to be complete with regard to life cycle phases [20]. Other datasets were therefore combined to provide as many diverse scenarios as possible, thus ensuring a mix of insect species and diets with the same system boundaries.

**Table 1** Studies used for the constructed insect protein value chain cases

| Insect | Principal datasets | Cradle to mill gate | | | | | Case | Comment |
|---|---|---|---|---|---|---|---|---|
| | | Rearing/cradle to farm gate | | | | Processing to insect meal | | |
| | | Direct insect gas emissions | Diet | Energy and utilities | Frass (avoided burdens) | | | |
| Mealworm (*Tenebrio molitor*) | Ooinincx and de Boer [25] | Data from Ooinincx, van Itterbeeck [39] | x | x | - | Data from Thévenot, Rivera [20] | 1a | Diet based on cereals. Diet and insect farming in the Netherlands, processing in France |
| | | | Data from Ooinincx, van Broekhoven [16] | x | - | | 1b | Diet based on vegetable waste food and brewery side stream. Diet and insect farming in the Netherlands, processing in France |
| | Thévenot, Rivera [20] | x | x | x | Data from Modahl, Lyng [48] | x | 2a | Diet based on cereals. Diet, insect farming and processing in France |
| | | x | Data from Ooinincx, van Broekhoven [16] | x | | x | 2b | Diet based on vegetable waste food and brewery side stream. Diet from the Netherlands, farming and processing in France |
| Black soldier fly larvae (*Hermetia illucens*) | Smetana, Palanisamy [21] | Data from Ooinincx, van Itterbeeck [39] | x<br>(frass not included) | | | | 3a | Diet based on side stream from brewery (Distiller's Dried Grains with Solubles—DDGS). Diet, insect farming and processing in Germany |
| | | Data from Ooinincx, van Itterbeeck [39] | Ingredients from Ooinincx, van Broekhoven [16], amounts from Tschirner and Simon [15] | x<br>(frass not included) | | | 3b | Replacing the diet in case 3a with vegetable waste food/brewery side stream resources and amounts. Using data from Tschirner and Simon [15] makes it possible to calculate the amount of feed and larvae needed. Diet from the Netherlands, insect farming and processing in Germany |

x From principal datasets, - Not included

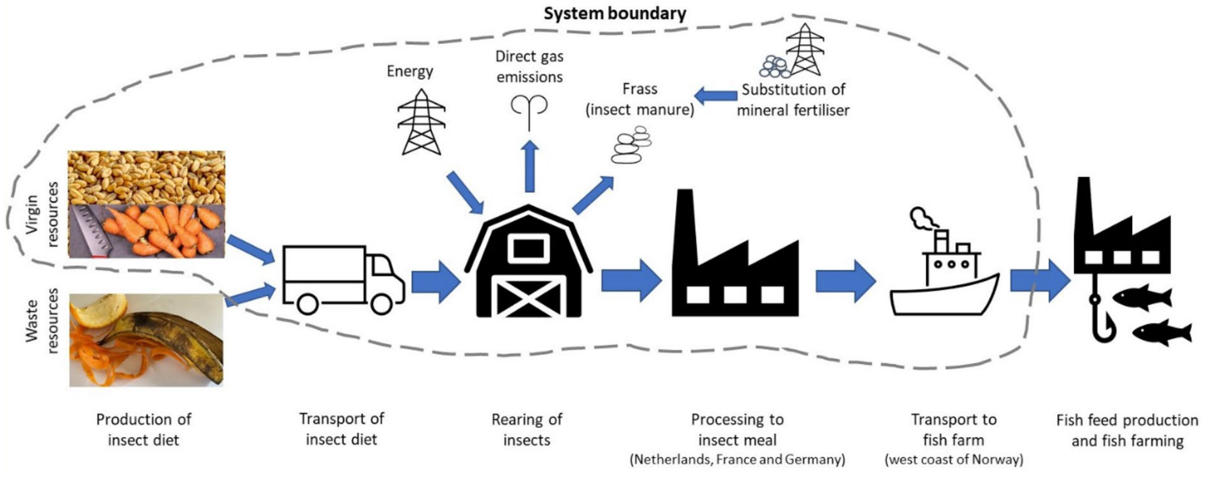


**Fig. 1** System boundaries for the insect protein value chains

The LCA studies mentioned in the review article of [9] have formed the basis for the work carried out in this study, supplemented by a number of other studies which have been examined for the purpose of finding additional life cycle inventory data.

Insects that are mass-reared for feeding purposes are classified as 'farmed animals' [21], and waste materials of animal origin allowed for feeding are therefore limited by EU Regulation [22]. Manure is only permitted as feed for insects in the manufacture of organic fertilisers or soil improvers. As a consequence, housefly larvae (Musca domestica) were omitted. This was because the relevant studies employed manure as diet, and the only waste considered here for insect diet in the production of feed, has been that from vegetables, to conform with present regulations.

Inventory data have been extracted from studies using solely original data. Focus has been on data for mealworm (Tenebrio molitor) and black soldier fly larvae (Hermetia illucens), as these are the species for which most LCA data are available and their diet is categorised as legitimate for feed production.

Although insects are produced for food and feed in such countries as Thailand, South Africa, China, Canada and the USA, no data from these regions were available and/or suitable, and the inventories used are all from case studies in Europe.

As part of the process of extracting inventories from published studies, reproduced results were created using, wherever possible, the same impact category methods as the original studies. These reproduced results were compared with the results given in the original studies to indicate whether any important input data was missing in the reproductions.

As a result of this process, three principal datasets were combined with data from four more studies, leading to six constructed cases in total. Both the original studies and the constructed cases are shown in Table 1.

The inventories from the original studies are given in Appendix 1. The inventories have been combined with background data from one single database, ecoinvent 3.5 allocation, cut off [23], to consistently model the insect protein value chains. The LCA tool applied in modelling the systems has been SimaPro version 9.0.0.47 multi user. In Appendix 2 the corresponding inventories for the constructed cases are given, together with the datasets used for modelling the foreground systems.

## 2.6 Data availability statement

All inventory data used in making the models in this study are included in this published article. See further description in Sect. 2.5 and the actual inventories used in Appendix 1.

## 2.7 Impact assessment

In this study, the Product Environmental Footprint Category Rules (PEFCR) for feed for food-producing animals [24] was applied in selecting the environmental indicators. Those emphasised as being most significant in the PEFCR, and therefore chosen for this study, are summarised in Table 2.

## 2.8 Other assumptions

The following data have been excluded:

**Table 2** Environmental impact categories

| Impact category | Unit | Name of method | Reference |
|---|---|---|---|
| Climate change | kg $CO_2$ eq | IPCC2013 100 year v.1.03 | IPCC [49] |
| Particulate matter | Disease incidences (described as *deaths* in UNEP/SETAC [50]) | Particulate matter (PM) model recommended by UNEP | UNEP/SETAC [50], pp.76–99, Fazio, Castellani [51], p. 16 |
| Terrestrial and freshwater acidification | mol $H^+$ eq | Accumulated Exceedance | Seppälä, Posch [52],<br>Posch, Seppälä [53],<br>Fazio, Castellani [51] |
| Land use | Points (dimensionless) | LANCA v.2.2 | Bos, Horn [54],<br>Fazio, Castellani [51], pp. 22–23 |
| Terrestrial eutrophication | mol N eq | Accumulated Exceedance | Seppälä, Posch [52],<br>Posch, Seppälä [53],<br>Fazio, Castellani [51] |
| Water use (scarcity) | $m^3$ water eq deprived | AWARE | UNEP/SETAC [50] |

*IPCC* Intergovernmental Panel on Climate Change, *UNEP* United Nations Environment Programme, *SETAC* Society of Environmental Toxicology and Chemistry, *LANCA* LANd use indicator value CAlculation in life cycle assessment, *AWARE* Available WAter REmaining

- Infrastructure for the foreground system (included for the background system).
- Land use for the processing plant (included for rearing/farming, and in the background system).

On the basis of the available literature scrutinised for this study, these deficiencies have been considered to be of minor importance. For those studies which have not provided any information regarding insect manure, or so-called frass, neither use nor treatment of frass have been included when modelling. Final transport of the insect meal has been added to the original data. The distances used in the modelling for transport of the insect meal to the west coast of Norway have been summarised in Table 3.

## 3 Results

The result section is split into three parts. Firstly, the reproducibility of previous studies is presented to display the variation between original and reproduced results. Secondly, the environmental impacts for different cases are presented together with a contribution analysis. In the third section, the results for insect proteins are compared with results for other protein sources.

### 3.1 Comparison between reproduced and original results

Reproduced results were made for the three principal studies. Although it was not always possible, an endeavour was made to apply the same impact methods and versions for the Life Cycle Impact Assessment (LCIA) as in the original studies. In some cases, the correct version of the impact methods was not available in the LCA tool employed to model the systems. In such cases, available (and more recent) versions of the same methods were applied. Appendix 3 describes the impact methods used for both the original and the reproduced studies, and comments are included where these differ.

In Fig. 2, only the results of the reproduced studies are shown. These are presented relative to the original results, which have been defined as 100% for each indicator in

**Table 3** Distances and means of transportation for insect meal delivered to the west coast of Norway (assumptions, based on Google maps and sea-distances.org)

| From | To | Distances | | |
|---|---|---|---|---|
| | | Rail | Sea | Road |
| Netherlands | Averøy on the west coast of Norway | – | Rotterdam—Averøy 1380 km | – |
| France | | – | Le Havre—Averøy 1710 km | Paris—Le Havre 200 km |
| Germany | | Berlin—Rostock 230 km | Rostock—Averøy 1450 km | – |

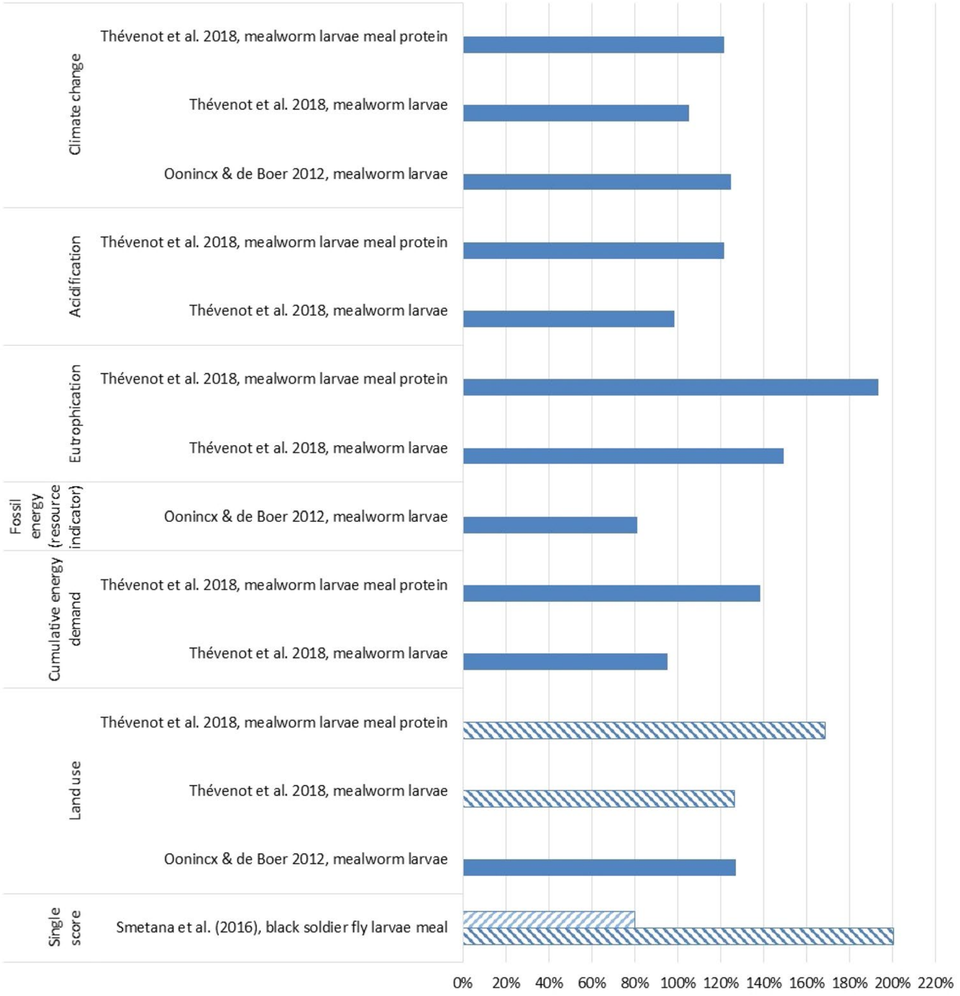


**Fig. 2** Results for the reproduced studies relative to the originals (original results are defined as 100% for each indicator in each study). The figure shows only the reproduced results

each study. Some original studies lacked information regarding the indicator method. Hence, for these there can be no certainty that the correct indicator version was used in reproducing the results. In these cases, the bars are shown in white and blue instead of just blue.

For those reproduced studies where the correct indicator versions have been used, the reproduced results vary between 81 and 193% of the original results. Of these, the eutrophication results from [20] are the least consistent with the original studies, being 149% and 193%. For climate change and acidification, however, the relative reproduced results are between 98 and 124%. In the original study, the production of the mealworm diet contributed 82% to the eutrophication potential, while in the reproduction the diet contributes 88%. The entire difference in eutrophication results is thus shown to relate to the modelling of the diet, which could imply that changes in the agricultural background processes are the reason for the eutrophication mismatch. The reproduced Cumulative Energy Demand (CED) results are 95% and 138% relative to the original results.

The results which have been reconstructed with the same LCIA methods as the originals have been climate change, land use and fossil energy on the basis of findings by Oonincx and de Boer [25]. These results are 124%, 81% and 127% relative to the originals, respectively. It is impossible to determine the exact acceptable deviation percentage, but natural systems often show a variance of 30% [26] and the uncertainty in life cycle inventories must be judged case by case [27, 28]. The conclusion was that the comparison of results from original studies with the reproductions ensured a level of similarity that is suitable for the presentation of the results from other environmental impact categories.

## 3.2 Results for the constructed cases

This section shows results for the six constructed insect protein cases for selected environmental impact categories and for the different life cycle stages. Table 4 shows the aggregated results (see Table 1 for details regarding each case).

**Table 4** Results for the environmental performance of rearing and processing insects into insect meal (per kg protein delivered to the west coast of Norway)

| FU = 1 kg protein in insect meal | | Climate change | Land use | Water scarcity | Respiratory inorganics | Acidification terrestrial and freshwater | Eutrophication terrestrial |
|---|---|---|---|---|---|---|---|
| Source | Case | kg $CO_2$-eq | pt | $m^3$ | disease incidences | mol $H^+$-eq | mol $N^-$-eq |
| Mealworm | 1a | 21.66 | 3658 | 41.41 | 1.3E−06 | 0.182 | 0.703 |
| Mealworm | 1b | 8.10 | 153 | 2.53 | 2.0E−07 | 0.028 | 0.088 |
| Mealworm | 2a | 6.31 | 1772 | 16.16 | 6.4E−07 | 0.083 | 0.316 |
| Mealworm | 2b | 2.37 | 151 | 4.38 | 1.8E−07 | 0.020 | 0.059 |
| Black soldier fly larvae | 3a | 3.81 | 99 | 7.19 | 1.7E−07 | 0.027 | 0.095 |
| Black soldier fly larvae | 3b | 3.15 | 48 | 2.91 | 1.2E−07 | 0.021 | 0.078 |

Figure 3 shows the extent to which the different life cycle steps contribute in each case, for each impact category.

The colours of the bars show that the most important contributing factors vary, not only across environmental impact categories, but also across cases within the same impact categories. This is especially marked for the climate change category where the diet (cases 1a and 2a), energy for rearing (case 2a) or processing to insect meal (cases 3a and 3b) is the most important factor, respectively. The figure does not, however, display the differences in absolute values between the different cases.

Absolute climate change results for the constructed cases, split into life cycle steps, are shown in Fig. 4.

There is a noticeable difference between the impacts for the mealworm and black soldier fly larvae cases when using the original diet (1a, 2a and 3a) and modified diet (1b, 2b and 3b). This is especially true for the mealworm cases (1 and 2) where the original diet is based on feed with a high economic value. When the diet is changed to waste resources, which have fewer environmental burdens allocated to them, while at the same time other inputs and outputs remain unchanged, the impacts are substantially decreased. For the two mealworm cases using the original

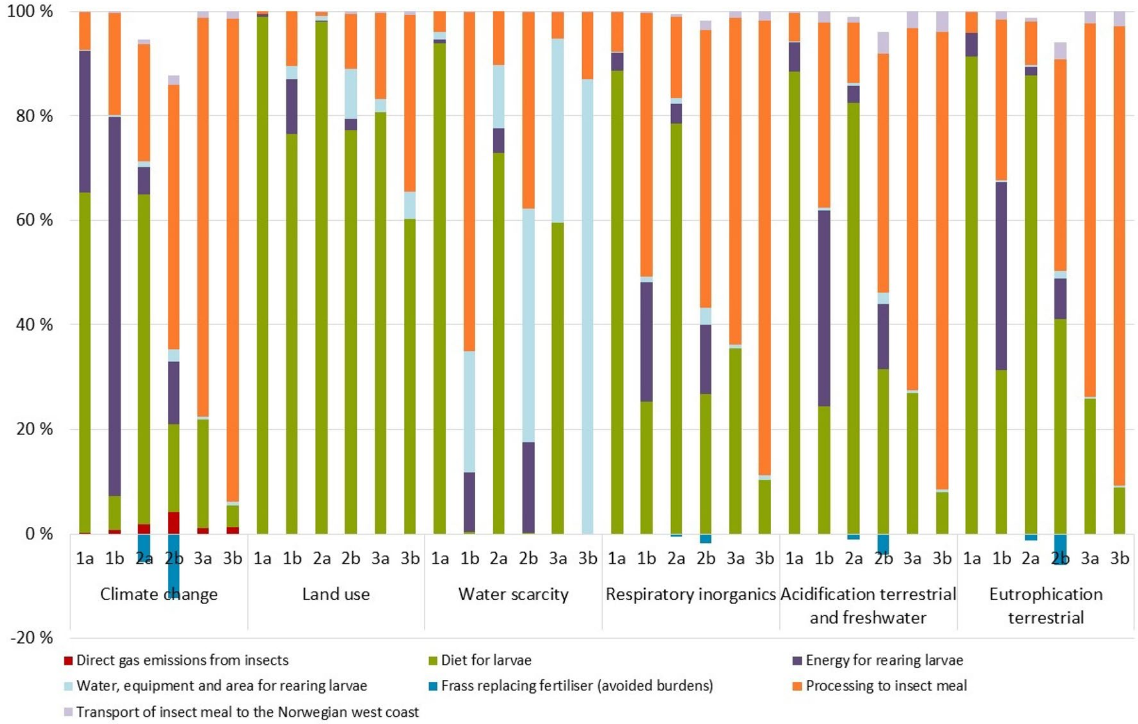


**Fig. 3** Contribution analysis for the environmental performance of rearing and processing insects into insect meal (for protein delivered to the west coast of Norway)

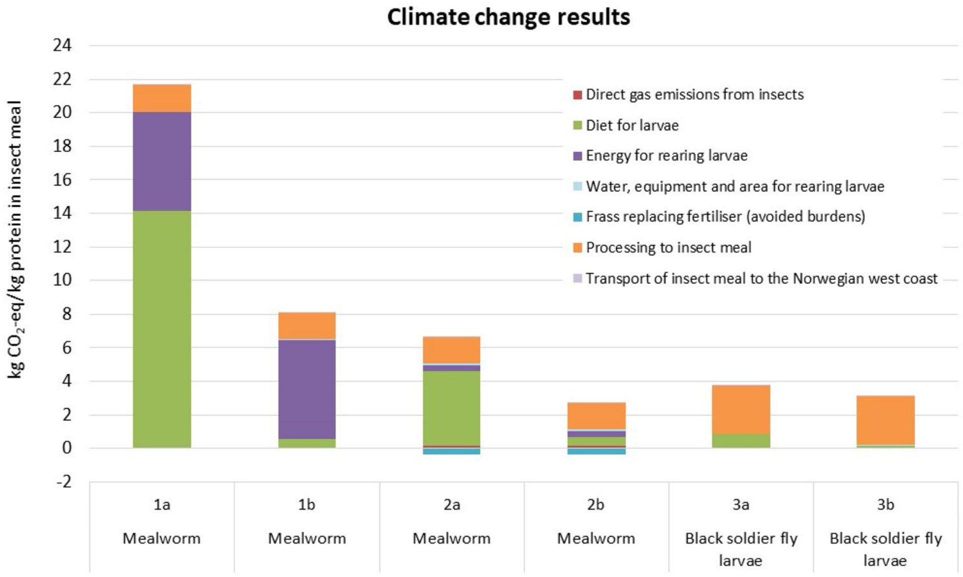


**Fig. 4** Climate change results for rearing and processing insects into insect meal (per kg protein delivered to the west coast of Norway)

diet (1a and 2a) the insect feed contributes most (65% to 99% depending on impact category). When employing the modified diet (1b and 2b), the sum of the energy for rearing and processing steps becomes most important (55% to 93%) for five of the six impact categories (for the land use category, diet is still the most burdensome step). The use of vegetable waste resources is also beneficial in feeding black soldier fly larvae (case 3b), but the effects are not as prominent, as the original diet case (3a) is already primarily using low economic value by-products.

According to literature, the most important parameters affecting the environmental footprint when rearing insects are insect species, insect diet and location/temperature. In this study, the analysed cases are too few to draw any statistical conclusions regarding species and location. It seems, however, clear that the insect diet forms an important parameter. The results have therefore been grouped into the following diet categories:

- Vegetables with high economic value (mixes of grains, flour, bran, vegetables and beer yeast)
- Vegetables with low economic value (distiller's dried grains with solubles, spent grains, cookie remains)

The results are grouped and shown for several indicators in Fig. 5.

For all indicators, a change from vegetables with a high economic value to those of a lower value, creates a reduction in the burdens. The effect is least pronounced for climate change, where the lowest impact for the diet with high economic value is smaller than the highest impact for the diet with low economic value. All the other impact categories show the vegetable diet with low economic value to be the better option for the entire range.

Land use is even more affected by the insect diet than the other indicators. For the mealworm cases, the change of diet to less economically valuable waste resources lead to a reduction of over 90% in the land use category. Another revelation is that in the analysed cases, the diet based on mixed grains, carrots and beer yeast (in 1a) is more burdensome for the land use indicator than cereal flour, wheat bran and beet pulp (in 2a) when rearing mealworms.

The utilising of frass (insect manure) to substitute mineral fertiliser was included for case 2a/b (mealworm) only. In these analyses, the effect was most pronounced for the climate change indicator, where the avoided burdens accounted for 12%-16% of the net burden.

Transport from Europe (the Netherlands, France, Germany) to the west coast of Norway makes only a marginal contribution to the results (less than 4.5% for all cases and indicators). Transport of feed for the insects is also of little importance (4% or less for the cases using the original diet), as are direct gas emissions from insects and substrate, contributing 5.5% to climate change in case 2b, and 2.1% or less in the other cases.

### 3.3 Comparison of protein results from the constructed insect cases with protein from more conventional sources

This sub-section compares the environmental performance of insect protein with other protein sources used for fish feed. A recent study presents the greenhouse gas emissions for salmon feed ingredients in Norway in 2017 [29]. According to this study, the four protein ingredients constituting the greatest proportion of feed formulated for farmed salmon in Norway in 2017 were soy protein (36% of

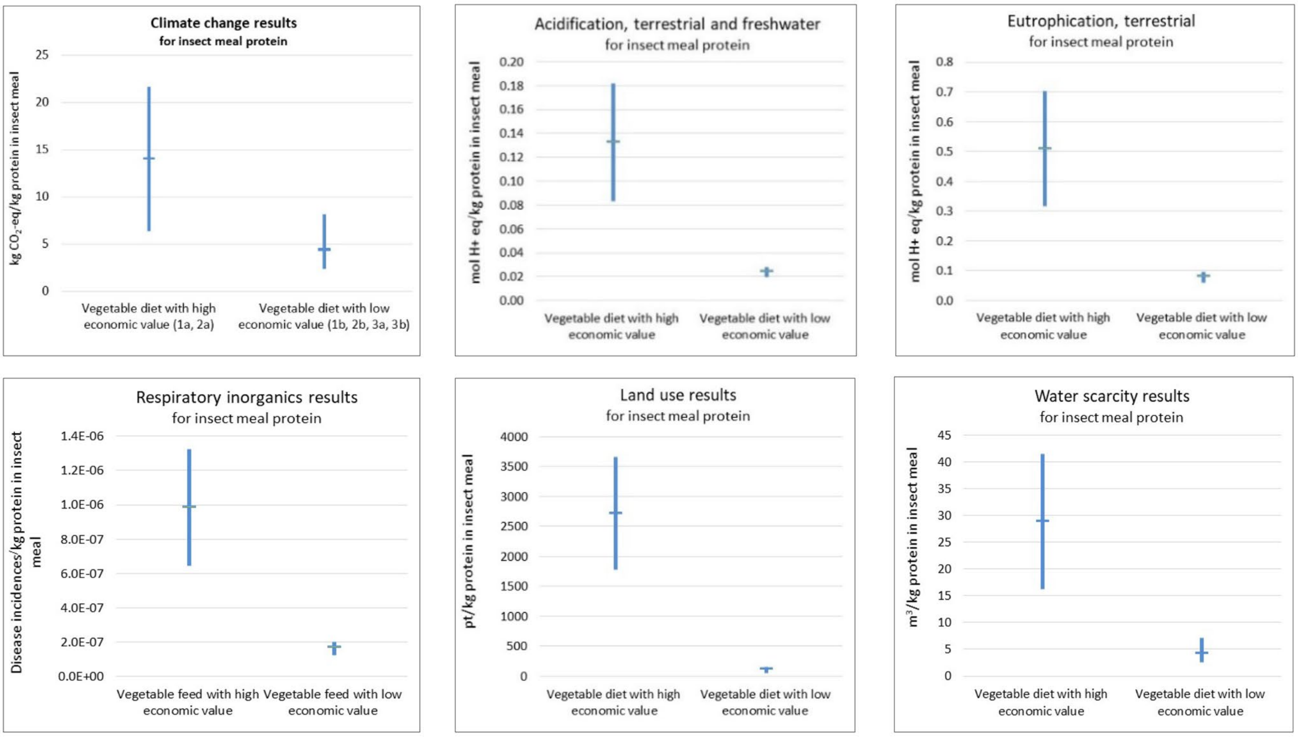


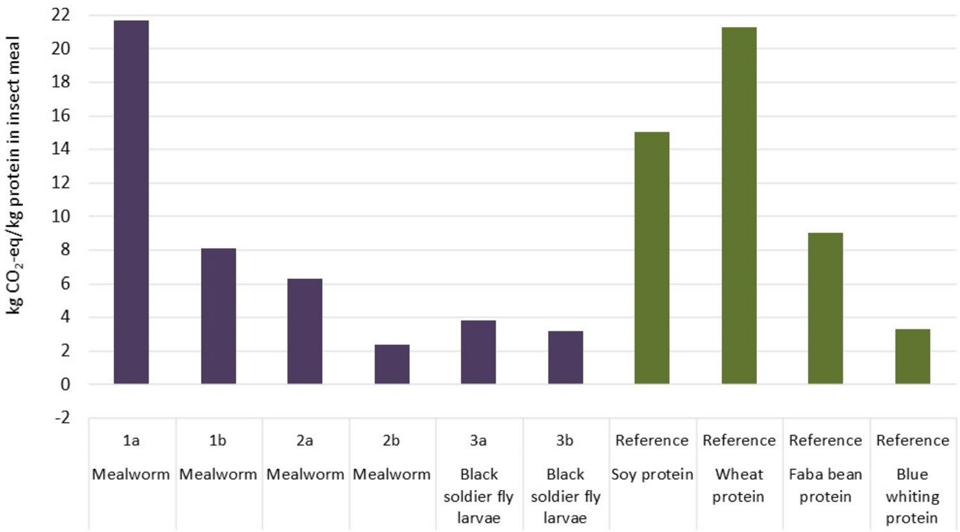
**Fig. 5** Results for rearing and processing insects into insect meal, presented for two groups based on insect diet (results given per kg protein delivered to the west coast of Norway). Number of insect cases: 6 in total

the protein ingredients), wheat protein (16%), blue whiting fish meal (10%) and faba beans (5%). Results from that study combined with assumed protein content of 40% for soy [30], 14% for wheat [31], 70% for blue whiting [32] and 31% for faba beans [33] give the following climate burdens for these protein ingredients; 15.0 (soy), 21.3 (wheat), 3.3 (blue whiting) and 9.0 (faba beans) kg CO$_2$-eq/kg crude protein.

Climate change results for the constructed cases are shown in Fig. 6 together with results for the most important salmon feed protein ingredients in Norway today.

Insect protein shows both the highest (1a) and the lowest (2b) impact on climate change. Thus, the grouped results for climate change are shown in comparison with the reference protein sources in Fig. 7.

**Fig. 6** Climate change results for insect meal (per kg protein delivered to the west coast of Norway) compared with reference products (per kg delivered to feed mill in Norway)



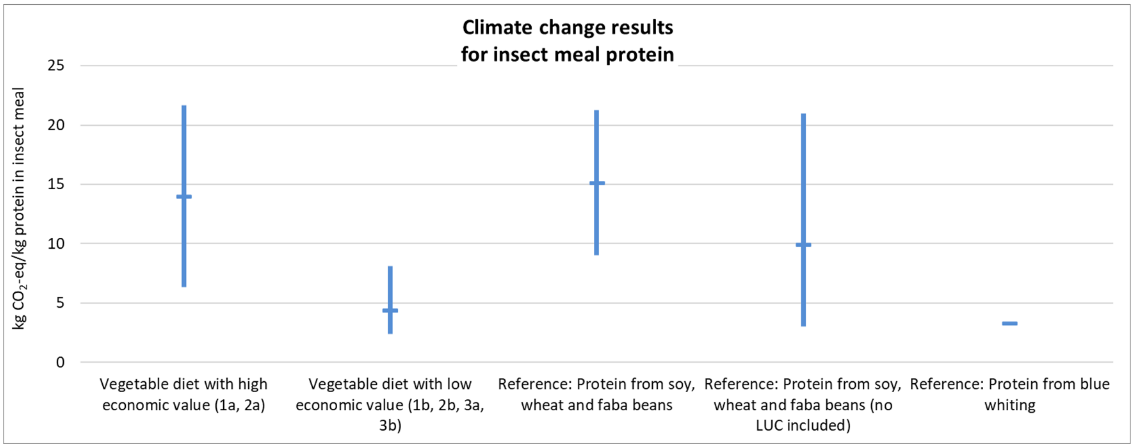


**Fig. 7** Climate change results for insect meal, presented for two groups based on insect diet (results given per kg protein delivered to the west coast of Norway) compared with reference products (per kg delivered to feed mill in Norway). Number of insect cases: 6 in total

Figure 7 shows that the climate change burdens for the low value diet insect proteins are the same or better than today's crop-based fish feed ingredients in Norway. Three of the four low value diet insect proteins can even compete with the blue whiting fish meal protein. For the farmed salmon feed ingredients, Land Use Change (LUC) contributes to the climate change burden. There is agreement that LUC is a major contributor to greenhouse gas emissions in agriculture [24] and that LUC should be included in LCA [34, 35], while there is at the same time discussion around the basis for calculation of LUC. A sensitivity analysis was therefore performed on the reference farmed salmon feed ingredients, removing the LUC contribution. The result shows, however, that excluding the LUC contribution made by the reference proteins does not affect the ranking of the different proteins.

It is relevant here to establish the amounts of these low-value vegetables, fruits and grains, and the potential for insect-based protein production employing these quantities as insect feed. A simplified calculation relating to wastage of vegetables and cereals in EU in 2013 [36] and the amounts required to produce mealworms [25] shows a theoretical potential annual production of 1.8 – 2.7 mill tonnes crude insect protein. The EU protein balance sheet [37] states that in 2016 the crude protein deficit for animal feed was 17.6 mill tonnes; thus proteins from insects can, in theory, provide 10–15% of the crude protein currently imported to the EU.

## 4 Discussion

The first three sub-sections here mirror the results section, with discussion of: (1) comparison between reproduced and original results; (2) the results for different environmental impacts in the constructed insect protein cases; and (3) comparison of insect proteins with other protein sources. In addition, there is a more general discussion of the environmental performance of protein sources and the way it should be documented.

### 4.1 Comparison of reproduced and original results

As the reproduced results are both below and above 1, relative to the original results, and no particular trend can be seen, the most likely reason for the greatest variations would appear to be the differing LCIA methods used in the originals and reconstructions. Where identical LCIA methods were used, the results show a maximum difference of 30% from the original which was deemed acceptable. For these, relative results of less than 1 arise most probably from missing data in the reconstruction, while relative results greater than 1 could stem from background data (from databases) becoming more comprehensive, and burdensome, as databases are updated. In addition, the mealworm diet information in the original studies was provided on a comparatively crude basis, mentioning the amounts of the principal feed groups (mixed grains, cereal flour and meals), but not the specific content within each group. The amount of mixed grains was, for example, given without details regarding the relative share of wheat bran, oats, soy, rye and corn, and this is a major source of error. The least consistent result was for eutrophication and this was 100% in relation to the insect diet. As land farming is frequently connected with eutrophication, it would seem fair to assume that agricultural background processes might have changed, causing a discrepancy in the eutrophication results.

The reconstruction of results gave no indication as to whether crucial input data were missing in this study's reproductions. As several of the LCIA methods, such as those for land use and respiratory inorganics, are employed for the first time, these results are difficult to assess because of a lack of previous results for comparison.

### 4.2 Constructed cases

In the original studies, neither data concerning infrastructure and land use for the processing plant, nor data on the use of antibiotics, vitamins and vaccinations, were available. These omissions are, however, regarded as minor in the available literature, as, for example by Halloran et al. [9] who made the assumption that the use of antibiotics in insect farming would have a negligible effect on the environmental burdens. The utilisation of frass was considered in two cases only (mealworm), and the results should therefore not be regarded as valid for the production of insect protein in general. Since, however, the effect of using frass did not turn out to be especially important (12%-16% at the most), and the effect of utilising animal manure is one of the primary contributors in other systems [38], the authors assume that omitting waste treatment of frass is of less importance. Direct gas emissions from insects and substrate were included in six of the eight cases. These gas emissions contributed less than 5.5% to climate change. These numbers should, however, be treated with care, as direct insect gas emissions are affected by several parameters (species, diet, temperature, stage of development, and activity level) [39], and little information is available about emissions from insects used in production systems.

The protein sources have been compared on the basis of crude protein content. A recent study [40] revealed that calculation of the protein content in insects based on a nitrogen-to-protein conversion factor of 6.25, as has often been the case, overestimates the protein content. This is due to the additional presence of non-protein nitrogen in the insects. When reproducing results from original studies and constructing new cases, the inventory data given by the studies in question have been employed [21, 25]. This also applies in the case of protein content. These studies have not referred to any conversion factors for protein; instead they have mentioned average percentage and generic composition of insects. It is, therefore, not clear on which basis the protein content has been calculated, and this is a cause for concern. Assuming that the constructed cases are based on a nitrogen-to-protein conversion factor which is too high, an uncertainty analysis was performed to show how the results changed. The climate change results for the constructed cases were divided by 0.76, corresponding to reducing the nitrogen-to-protein conversion factor from 6.25 to 4.76 [40]. The average climate change result for the low value diet insect proteins then showed a change in the ranking in comparison with blue whiting. Nevertheless, one of the insect proteins still had a lower climate change burden than blue whiting, and, when compared with the average crop-based fish feed ingredients, the low value diet insect proteins still had a better modified average climate change result. This was true even when no LUC was included for the crop-based proteins.

The composition of various proteins and anti-nutritional components could vary between the different insect species, however these qualities have not been taken into account. A review paper by Pinotti and Ottoboni [41] showed, nonetheless, that the fatty acid profile of black soldier fly larvae is only affected by the substrate to a limited extent.

### 4.3 Insect protein from constructed cases compared with conventional proteins

Insect producers' websites and news articles refer to the insect diet as 'left-overs'[42, 43]; plant waste [44]; food waste [44, 45] or low-grade food waste [46]; wet organic waste [42]; food industry by-products, and vegetables, fruits and grains from food production and agricultural refining [47]. The authors therefore recommend that in further comparison with other protein sources, the results for the cases in the 'Vegetable diet with low economic value' category are employed.

The results showed that proteins from insects fed on agricultural wastes can, in theory, provide between one-sixth and one-tenth of the imported protein feed in the EU. Although such insect proteins cannot provide a total solution to filling the protein gap, they can form an important part. One should, however, also be aware that many initiatives exist both for the reduction of waste from food value chains and for valorising it for different purposes. As a result, feed for insects that would be regarded as having low value today could become more scarce and gain higher value within the near future. When economic allocation is used for the LCA, this becomes even more important.

The EU seeks a greater level of protein self-sufficiency, and protein from insects has been put forward as a possible alternative source. The insect proteins that are most likely to be utilised as fish feed, having a diet based on vegetables with low economic value, have a climate change burden in line with and well below these crop-based fish feed ingredients. Three of the four insect proteins also compete with the blue whiting fish meal protein. Some of the climate change burden for the farmed salmon feed ingredients were created by LUC, but even when assuming no LUC for the farmed salmon feed ingredients, these conclusions for the insect proteins still hold.

The comparison between insect proteins and other protein sources is only performed for the climate change category. Although the insect proteins show comparable performance in the climate category, closer scrutiny is required to ensure that they also have comparable performance in the other environmental impact categories.

### 4.4 The contribution of LCA method choices

For all indicators, the burden for insect protein is considerably lowered when insects are fed with a diet of low-value vegetables ('waste') instead of high-value vegetables. The effect is most pronounced for the land use indicator and is least for climate change. This leads to results which indicate that insect protein has the potential to compete environmentally with existing protein sources for fish feed. It cannot, however, be taken for granted that any insect protein is environmentally beneficial, as this comparison has been made with a limited number of cases. Another important precondition is the choice of allocation method in the background database for the insect diets. As the background database uses economic allocation, low-value vegetables ('waste') are given a lower burden than if the allocation had been based on mass. The choice of allocation method is not, however, purely an issue for the insect protein results. The same effects can occur for the conventional proteins, as in certain cases these are also co-produced with other products, and allocation is thus applied in the background database.

The choice of functional unit could have a major impact on the results. Comparisons shown here are based on a functional unit defined as 1 kg of crude protein. The dependency on the way crude protein is calculated or approximated creates a problem. This is probably most pronounced for the insects, as they are known to contain non-protein nitrogen, but it could also be of relevance for the conventional proteins. The protein content of plants and animals shows variation across species and locations and should therefore be specified for particular protein sources. In addition, crude protein is a generic term that hides the actual performance of the protein source for the animal being fed. Different animals require different compositions of proteins, and the protein sources might comprise so-called anti-nutritional factors or have a taste or a level of digestibility that affects the utilisation of the protein source in a feed. If the protein source is used for feed for food-producing animals, a better functional unit would relate to the growth and nutritional value of the animal being fed; even better would be a connection to the nutritional value for humans.

System boundaries connected to time, location, and technologies are important for results, and especially for emergent production systems such as those for insect proteins. Important parameters could and will change as experience is gained and production scaled up. At the same time, there will be changes in underlying energy and logistics systems, and these will in turn alter the ranking between different protein sources. Data will have to be updated for insect proteins as well as other proteins to ensure valid comparisons in the future.

This study employed environmental impact categories presented as being especially relevant in the PEFCR for food for feed-producing animals [24]. Some of these categories are connected to immature LCIA methods where the uncertainty of the model itself is high and the inclusion of data might either vary across value chains or be too scarce. Only experience will reveal whether the categories show the all-important and essential effects. This study makes a contribution towards the gaining of such experience.

## 5 Conclusions

The aim of the study has been to transform existing knowledge on insect proteins into LCAs, so as to enable comparisons with more conventional proteins. This has been achieved by reproducing results from previously published and peer-reviewed studies, and by combining inventories in LCA models using consistent system boundaries, background data and indicators. The PEFCR for "Feed for food-producing animals" [24] have been applied to secure similar treatment of different production chains. The focus has been on insect protein which has the potential to be used as fish feed.

This study is one of the first attempts at using proposed environmental impact categories for Product Environmental Footprints (PEF). Employment of the same database and similar choices of method in the LCA modelling has ensured the comparability of different insect protein sources across environmental impact categories.

As the insect diet is shown to dominate in the results, a practicable grouping would be based on the insect diet: vegetables with high economic value and vegetables with low economic value. In the 'high economic value' cases the insect diet makes the greatest contribution. The burdens decrease when the diet is changed to a basis of low value resources. The effect is most pronounced for the land use indicator and least for climate change.

For the two cases where frass substituted mineral fertiliser, the net climate change results were reduced by 12%. In addition, direct gas emissions from insects and substrate seem to be of little importance, although these numbers should be used with caution as there are major uncertainties. Transport from Europe to the west coast of Norway contributed only marginally to the environmental burdens for insect meal protein.

Insect protein based on vegetables with low economic value have the potential to compete environmentally with existing protein sources for fish feed. It is important to note that these results are affected by the choice of allocation method in the background database for the insect diet (economic allocation) as well as by assumptions made regarding protein content in insects. Proteins from insects can in theory provide 10—15% of the imported crude protein for feed to the EU.

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**Author contributions** ISM performed the literature search and designed the LCA models. Analysis of the results and the writing of the manuscript were carried out by both ISM and AB.

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**Data availability** The lead author affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects have been omitted; and that any discrepancies from the study as planned have been explained. All input data used and generated during this study are included in this published article and its appendices.

## Declarations

**Conflict of interest** Author Ingunn Saur Modahl declares that she has no conflict of interest. Author Andreas Brekke declares that he has no conflict of interest.

**Research involving human and animal rights** This article does not contain any studies with human participants or animals performed by any of the authors.

## Appendix 1

See Table 5.

**Table 5** Life cycle inventory data given in the examined literature

| Insect species | Study and system boundaries | Rearing of insects (cradle to farm gate) | Production of insect meal and oil (processing) | Comments |
|---|---|---|---|---|
| Mealworm (*Tenebrio molitor*) | Oonincx, van Itterbeeck [39]: direct gas emissions form insects | Direct insect emissions (per kg mass gain):<br>$CO_2$: 1031 ± 349 g<br>$CH_4$: 0.1 ± 0.03 g<br>$N_2O$: 25.5 ± 7.7 mg<br>$NH_3$: 1 ± 2.0[a] | | Experimental data. The data include emissions of insects, insect diet and substrate. The study includes data also for several other insect species |
| | Oonincx and de Boer [25]: cradle to farm gate (mealworm) | Input:<br>Carrots: 260,000 kg/year<br>Mixed grains (wheat brain, oats, soy, rye, corn and beer yeast): 182,000 kg/year<br>Egg trays: 262 kg/year<br>Gas: 811,200 MJ/year<br>Electricity: 187,200 MJ/year<br>Water: 211 m3/year. Farm: 1<br>Direct insect emissions:<br>Data from [39]<br>Output:<br>Animal (insects): 83,200 kg/year<br>Feed Conversion Rate (FCR) for concentrates (excluding the carrots): 2.2 kg/kg of live weight[b] | | Coproduction with superworm (*Zophobas morio)*. For fresh larvae:<br>Dry Matter (DM) content: 38%<br>Crude protein: 53% of DM<br>Edible portion: 100%<br>No allocation (or burdens) connected with the insect manure (frass) or expired breeder animals are given. A proxy distance (55 km) for transporting the insect diet has been assumed by NORSUS. Use of area has been included by NORSUS, using data from [20] |
| | Oonincx, van Broekhoven [16]: diet conversion and survival experiments cradle to farm gate (laboratory, mealworm) | Input, high protein, high fat (HPHF) diet[c]:<br>60% spent grains, 20% beer yeast and 20% cookie remains<br>FCR[d]: 3.8 ± 0.63 kg/kg weight gain<br>Efficiency of Conversion of Ingested food (ECI)[e] (dry matter conversion of ingested food): 12 ± 2.7%<br>No energy data given | | The diet has been assumed low-cost by NORSUS. Transport included by using marketbased data. Composition of mealworm (killed by freezing):<br>DM content: 41.5 ± 0.37%<br>Crude protein: 53.6 ± 0.45% of DM |

**Table 5** (continued)

| Insect species | Study and system boundaries | Rearing of insects (cradle to farm gate) | Production of insect meal and oil (processing) | Comments |
|---|---|---|---|---|
| | Thévenot, Rivera [20]: cradle to mill gate (mealworm meal) | Input:<br>Cereal flours (wheat, maize): 15.5%<br>Meals (rape seed, sunflower, soybean): 24.5%<br>Wheat bran: 50%<br>Sugar beet pulp: 10%<br>Direct insect emissions:<br>Values given in mass per kg body mass per day:<br>$CH_4$: 1.06 ± 1.02 mg<br>$N_2O$: 0.87 ± 0.35 mg<br>Rearing for 11–13 weeks. 12 weeks gives (per kg body mass):<br>$CH_4$: 89.04 ± 85.68 mg<br>$N_2O$: 73.08 ± 29.4 mg<br>Output:<br>Manure: 90% of the mass of larvae harvested, with a DM > 90%. Has a C:N ratio of 13,8 and a Nitrogen/Phosphorus/Potassium (NPK) content of 29‰, 34‰ and 22‰<br>FCR: 1.98 kg/kg<br>For 1 kg larvae at farm gate:<br>Diet: 1.983 kg (wet)<br>Manure: 0.900 kg<br>Electricity: 1.152 kWh<br>Tap water[f]: 8.627 m3<br>Equipment[g]: 0.005 kg<br>Rearing plant: 0.016 m2 | For 1 kg of larvae meal at processing plant gate[h]:<br>Mealworm larvae: 3.846 kg<br>Electricity: 8.940 kWh<br>Transportation: 2.231 tkm<br>Equipment: 0.009 kg[i]<br>Raw sewage sludge: 2.538 kg | Economic allocation between meal and oil in the processing step. The meal has been allocated 88.5% of the burdens and 11.5% is allocated to oil<br>Calculation by NORSUS: Using data from [16],<br>41.5% DM for mealworms leads to 1.596 kg DM when using 3.846 kg fresh mealworm. This is split between larvae meal (1 kg) and oil, hence 0.596 kg oil per kg larvae meal<br>The insect manure (frass) has properties similar to poultry manure and can be used as fertiliser (not included in the original study). Avoided burdens have been included by NORSUS<br>The tap water amount has been corrected [55]<br>A proxy distance for insect diet transport has been included (55 km)<br>Composition of mealworm meal:<br>Moisture: 8%<br>Protein: 65%<br>Lipids: 13% |
| Black soldier fly larvae (*Hermetia illucens*) | Oonincx, van Broekhoven [16]: insect diet conversion and survival experiments cradle to farm gate (laboratory, black soldier fly larvae) | Input:<br>60% spent grains, 20% beer yeast and 20% cookie remains (HPHF diet)[j]<br>FCR[k]: 1.4 ± 0.12 kg/kg weight gain<br>ECI[l] (dry matter conversion of ingested food): 24 ± 1.5%<br>No energy data given | Calculation by NORSUS: Tschirner and Simon [15] use 6.3 kg DDGS per kg larvae yield. Smetana, Palanisamy [21] use 25.46 kg DDGS per kg larvae meal. This means that approx 25.46/6.3 = 4.04 kg black soldier fly larvae is needed to produce 1 kg larvae meal | The given diet has been assumed low-cost by NORSUS<br>Composition of black soldier fly larvae:<br>DM content: 32.9 ± 1.86%<br>Crude protein: 46.3 ± 0.93% of DM<br>Killed by freezing |
| | Tschirner and Simon [15]: cradle to farm gate (laboratory, black soldier fly larvae) | Input per kg larvae yield:<br>DDGS: 6.3 ± 2.5 kg DM/kg wet mass larvae<br>No energy data given | | Composition of black soldier fly larvae fed on DDGS:<br>DM content: 30.2 ± 1.03%<br>Crude protein: 44.6 ± 0.63% of DM |

**Table 5** (continued)

| Insect species | Study and system boundaries | Rearing of insects (cradle to farm gate) | Production of insect meal and oil (processing) | Comments |
|---|---|---|---|---|
| | Smetana, Palanisamy [21]: cradle to mill gate (black soldier fly larvae meal) | Input:<br>DDGS: 25.46 kg<br>Electricity: 17.13 MJ<br>Heat: 5.1 MJ (assumed natural gas)<br>Tap water: 66.93 kg<br>Direct insect emissions:<br>Data from [39]<br>Output:<br>Protein powder (dried and defatted larvae meal): 1 kg<br>Fat: 0.9 kg | | Killed by freezing. Content of larvae meal:<br>10% moisture<br>60% protein<br>10% fat<br>Mass allocation was used in the foreground system, hence mass allocation between protein and fat has been assumed by NORSUS. Residuals were dried for further use as fertilisers. However, the potential environmental benefit seems not to have been included in the LCA modelling. Use of area included by NORSUS, using data from [20]. Transport has been included for the insect diet by using marketbased data |

[a] The correct number is somewhat unclear. In Table 4 of [9] this number is given. However, the unit is different from the other gas emissions given in the same table, and the table heading indicates the same unit for all gases. In addition, the discussion section states, 'We conclude that …. and *T. molitor* probably did not emit $NH_3$.' Hence, the number could be (a) 1 ± 2.0 mg/kg mass gain; (b) 1 ± 2.0 mg/day/kg mass gain; (c) 0. In the modelling, option (c) has been chosen.

[b] For calculation of dry matter values, one can assume 12% for carrots and 83% for mixed grains:'Feed values' (carrots): https://www.dairynz.co.nz/feed/supplements/feed-values/; 'Average Dry Matter Percentages for Various Livestock Feeds' (mixed grains): https://www.ccof.org/sites/default/files/Feed%20Type%20DMI%20Table%20Final.pdf

[c] Of the four diets, this has been chosen as it is assumed to be the one most similar to DDGS and because this diet led to the fastest insect development both for mealworm and black soldier fly. No carrots were provided in this diet. The diets were based on by-products from food manufacturing

[d] Fresh weight basis

[e] Weight gained/weight if ingested food, on a dry matter basis

[f] According to [6], 8.627 m3 tap water is used per kg larvae at farm gate. Personal correspondence with Alexandre Thévenot (27/8–19) 55.Thévenot, A., *On water use for rearing mealworms (personal communication)*. 2019. revealed that this number is wrongly written in the paper (the unit is incorrect). The correct number is 8.627 kg per kg larvae

[g] Mainly steel

[h] Larvae meal has been allocated 88.5% of the burdens (= input values). Hence, the total input of larvae, electricity, transportation, equipment and sludge is higher than the numbers given here

[i] Mainly steel

[j] Of the four diets, this has been chosen as it is assumed to be the one most similar to DDGS and because this diet led to fastest insect development both for mealworm and black soldier fly. The diets were based on by-products from food manufacturing

[k] Fresh weight basis

[l] Weight gained/weight if ingested food, on a dry matter basis

## Appendix 2

See Table 6.

**Table 6** Inventory tale for the constructed insect protein value chain cases, including datasets used for modelling

| Case | Cradle to mill gate | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rearing/cradle to farm gate | | | | | | | | | Processing to insect meal | | |
| | Direct insect gas emissions | | Diet | | | Energy and utilities | | | Frass (avoided burdens) | | | |
| 1a | 1031 | g $CO_2$ (bio)/kg fresh mealworm | 59 | % | Carrots: Carrot (NL)\|carrot production\|Cut-off, U (ecoinvent) | 2.25 | MJ/kg fresh mealworm | Electricity: Electricity, low voltage (NL)\|market for\|Cut-off, U (ecoinvent) | Not included | 32.18 | MJ/kg mealworm meal | Electricity: Electricity, low voltage (FR)\|market for\|Cut-off, U (ecoinvent) |
| | 0.1 | g $CH_4$/kg fresh mealworm | 7 | % | Bran: Wheat bran, from dry milling, at plant/NL Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | 9.75 | MJ/kg fresh mealworm | Gas for heating: Heat, central or small-scale, natural gas (CH)\|market for heat, central or small-scale, natural gas\|Cut-off, U (ecoinvent), assuming 90% efficiency from gas to heat | | 2.23 | tonne*km/kg mealworm meal | Transportation (equipment and insect feed): Transport, freight, lorry 7.5–16 metric ton, euro4 (RER)\|market for transport, freight, lorry 7.5–16 metric ton, EURO4\|Cut-off, U (ecoinvent) |
| | 25.5 | mg $N_2O$/kg fresh mealworm | 7 | % | Oat grain: Oat grain (GLO)\|market for\|Cut-off, U (ecoinvent process modified by removing transport) | 2.54 | kg/kg fresh mealworm | Tap water: Tap water (Europe without Switzerland)\|market for\|Cut-off, U (ecoinvent) | | 0.009 | kg/kg mealworm meal | Equipment, mostly steel: Steel, low-alloyed (RER)\|steel production, converter, low-alloyed\|Cut-off, U (ecoinvent) |
| | | | 7 | % | Soybean grain: Soybean, Swiss integrated production (CH)\|market for soybean, Swiss integrated production\|Cut-off, U (ecoinvent) | 0.003 | kg/kg fresh mealworm | Egg trays: 50% Containerboard, fluting medium (RER)\|market for containerboard, fluting medium\|Cut-off, U (ecoinvent) and 50% Solid bleached board (GLO)\|market for\|Cut-off, U (ecoinvent) | | 2.54 | kg/ kg mealworm meal | Treatment of raw sewage sludge: Raw sewage sludge (CH)\|market for raw sewage sludge\|Cut-off, U (ecoinvent) |
| | | | 7 | % | Rye grain: Rye grain, feed, organic (GLO}\|market for\|Cut-off, U (ecoinvent process modified by removing transport) | | | | | 3.85 | kg fresh mealworm larvae/kg mealworm meal | |

**Table 6** (continued)

| Case | Cradle to mill gate | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Rearing/cradle to farm gate | | | | | | Processing to insect meal | |
| | Direct insect gas emissions | Diet | | | Energy and utilities | Frass (avoided burdens) | | |
| | | 7 | % | Maize grain: Maize grain, feed (GLO)\|market for\|Cut-off, U (ecoinvent process modified by removing transport) | For land transformation and occupation, data from case 2a is used | | 0.60 | kg mealworm larvae oil is co-produced for each kg mealworm meal |
| | | 7 | % | Beer yeast (proxy process): Fodder yeast (CH)\|ethanol production from whey\|Cut-off, U (ecoinvent) | | | 88.5% | Share of burdens allocated mealworm meal. Based on economic allocation, 11.5% of the burdens are allocated to oil and 88.5 is allocated mealworm meal |
| | | 55 | km | Transport by lorry for all ingredients | | | | |
| | | 5.34 | kg wet weight diet/kg fresh mealworm | | | | 65% | Protein content of mealworm meal |
| 1b | Same emission data as for case 1a | 0.6 | kg/kg wet weight diet | Spent grains, incl transport: Brewer's grains, consumption mix, at feed compound plant/NL Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | Same energy and utilities data as for case 1a. For land transformation and occupation, data from case 2a is used | Not included | Same processing data as for case 1a | |

**Table 6** (continued)

| Case | Cradle to mill gate | | | | | | |
|---|---|---|---|---|---|---|---|
| | Rearing/cradle to farm gate | | | | | | Processing to insect meal |
| | Direct insect gas emissions | Diet | | | Energy and utilities | Frass (avoided burdens) | |
| | | 0.2 | kg/kg wet weight diet | Proxy process for 'waste' beer yeast: Distiller's Dried Grains with Solubles (CH)\|ethanol production from potatoes\|Cut-off, U (ecoinvent)<br>Transport data from: Brewer's grains, consumption mix, at feed compound plant/NL Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | | | |
| | | 0.2 | kg/kg wet weight diet | Cookie remains, assumed free of charge, incl transport: No burdens for resource. A transport distance of 55 km is used, which is the mean value for transport of spent grains and beer yeast | | | |
| | | 3.8 | kg wet weight diet/kg fresh mealworm | | | | |

**Table 6** (continued)

| Case | Cradle to mill gate | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Rearing/cradle to farm gate | | | | | | | | | Processing to insect meal |
| | Direct insect gas emissions | | Diet | | | Energy and utilities | | | Frass (avoided burdens) | |
| 2a | 89.04 | g $CH_4$/kg fresh mealworm | 8 | % | Wheat flour: Wheat flour, from dry milling, at plant/FR Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | 4.15 | MJ/kg fresh mealworm | Electricity: Electricity, low voltage (FR)\|market for\|Cut-off, U (ecoinvent) | 0.0235 kg N in synthetic fertilizer is avoided per kg fresh mealworm (0.9 kg wet weight frass/kg larvae × 0.9 kg DM frass/wet weight frass × 0.029 kg N/kg DM frass). Avoided process modelled in separate project in NORSUS [38] (Fertilizer, NPK synthetic, Norway, per kilo N, 2010), based on data from Yara | Same processing data as for case 1a |
| | 73.08 | mg $N_2O$/kg fresh mealworm | 8 | % | Maize flour: Maize flour, from dry milling, at plant/FR Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | 8.63 | kg/kg fresh mealworm | Tap water: Tap water (Europe without Switzerland)\|market for\|Cut-off, U (ecoinvent) | | |
| | | | 8 | % | Rapeseed meal: Rape meal (Europe without Switzerland)\|rape oil mill operation\|Cut-off, S (ecoinvent) | 0.005 | kg/kg fresh mealworm | Equipment (steel): Steel, low-alloyed (RER)\|steel production, converter, low-alloyed\|Cut-off, U (ecoinvent) | | |
| | | | 8 | % | Sunflower meak: Sunflower seed meal, from crushing (solvent), at plant/FR Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | | | | | |

**Table 6** (continued)

| Case | Cradle to mill gate | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Rearing/cradle to farm gate | | | | | | | | Processing to insect meal |
| | Direct insect gas emissions | Diet | | | Energy and utilities | | | Frass (avoided burdens) | |
| | | 8 | % | Soybean meal: Soybean meal (RER)\|soybean meal and crude oil production\|Cut-off, U (ecoinvent) | 0.016 | $m^2$/kg fresh mealworm larvae | For rearing plant: Inputs from nature: Transformation, from unknown | | |
| | | 50 | % | Wheat bran: Wheat bran, from dry milling, at plant/FR Economic (modified Agri-footprint process using original inventory with ecoinvent input processes) | 0.016 | $m^2$/kg fresh mealworm larvae | For rearing plant: Inputs from nature: Transformation, to industrial area | | |
| | | 10 | % | Sugar beet pulp: Sugar beet pulp (CH)\|beet sugar production\|Cut-off, U (ecoinvent) | 0.004 | $m^2$/kg fresh mealworm larvae | For rearing plant: Occupation, industrial area 0,016 $m^2$ for 1 kg mealworm larvae at farm gate. For occupation: Have multiplied with the lifetime of the larvae (reared for 12 weeks, which is 12/52 year) | | |
| | | 55 | km | Transport by lorry for all ingredients | | | | | |
| | | 1.98 | kg wet weight diet/kg fresh mealworm | | | | | | |

**Table 6** (continued)

| Case | Cradle to mill gate | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Rearing/cradle to farm gate | | | | | | Processing to insect meal | | |
| | Direct insect gas emissions | Diet | | | Energy and utilities | Frass (avoided burdens) | | | |
| 2b | Same emission data as for case 2a | Composition, datasets, transport and amount: same as for case 1b | | | Same energy and utilities data as for case 2a | Same avoided burdens as in case 2a | Same processing data as for case 1a | | |
| 3a | Same emission data as for case 1a | 100 | % | DDGS incl transport: Distiller's Dried Grains with Solubles (GLO)\|market for\|Cut-off, U (ecoinvent) | Energy and utilities for rearing are included in the processing step. For land transformation and occupation, data from case 2a is used | Not included | 17.13 | MJ/kg BSFL meal | Electricity: Electricity, low voltage (DE)\|market for\|Cut-off, U (ecoinvent) |
| | | | | | | | 5.1 | MJ/kg BSFL meal | Gas for heating: Heat, central or small-scale, natural gas (CH)\|market for heat, central or small-scale, natural gas\|Cut-off, U (ecoinvent), assuming 90% efficiency from gas to heat |
| | | | | | | | 66.93 | kg/kg BSFL meal | Tap water: Tap water (Europe without Switzerland)\|market for\|Cut-off, U (ecoinvent) |
| | | | | | | | 4.04 | kg fresh BSF larvae/kg BSF larvae meal | |
| | | | | | | | 0.9 | kg BSF larvae oil is co-produced for each kg BSF larvae meal | |
| | | | | | | | 52.6% | Share of burdens allocated BSFL meal. The original study allocated 47.4 of the burdens to oil and 52.6% to BSFL meal | |
| | | 6.3 | kg wet weight diet/kg fresh Black Soldier Fly Larvae (BSFL) | | | | 60% | Protein content of BSFL meal | |
| 3b | Same emission data as for case 1a | Composition, datasets and transport: same as for case 1b | | | Energy and utilities for rearing are included in the processing step. For land transformation and occupation, data from case 2a is used | Not included | Same processing data as for case 3a | | |
| | | 1.4 | kg wet weight diet/kg fresh BSF larvae | | | | | | |

The original names of the datasets have been used in this table to ensure correct reference. Hence, abbreviations have been written without explanations in the table. These abbreviations are used in the dataset names above: *S* system process, *U* unit process, *NL* Netherlands, *GLO* global, *RER* Europe, *CH* Switzerland, *FR* France, *DE* Germany

## Appendix 3

See Table 7.

**Table 7** Impact methods used in the original studies and for reproducing the results

| | Indicator | Comment to method used in the original study | Comment to method used to reproduce the results |
|---|---|---|---|
| Oonincx and de Boer [25] | Climate change | A simple method has been used by the authors. Only three substances have been taken into account ($CO_2$, $CH_4$ and $N_2O$), and the characterisation factors are in line with IPCC 2007 | A method was made to match that used by the original study |
| | Fossil energy use | No reference to any specific method for fossil energy use | Have used the Abiotic depletion (fossil fuels) category in CMLIAb v3.05 |
| | Land use | Land use seems to be without charactersation | A method without characterisation was created to match the one used by the original study |
| Thévenot, Rivera [20] | Climate change, acidification and eutrophication | CML-IA baseline 2000 v2.03 | Updated versions of these methods (from CML-IA baseline 2000 v3.05) were used to reproduce the results. IPCC 2013 100 year v.1.03 was used for climate change |
| | Cumulative energy demand | VDI 1997 | The Cumulative Energy Demand v1.11 from ecoinvent (November 2018), updated with missing substances, have been used |
| | Land use | Assumed to be CML-IA baseline 2000 v2.03 | The authors do not have access to the correct version of this method. Hence, 'Land competition' in the non-baseline version of CML-IA 2000 v3.04 was used |
| Smetana, Palanisamy [21] | Single score | ReCiPe Endpoint (H) v1.08/Europe ReCiPe H/A (from 2008) | As the authors did not have access to the old version of this method, two newer versions were tested; one based on the 2008 method and one on the 2016 method:<br>ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/A (based on the 2008 version)<br>ReCiPe 2016 Endpoint (H) v 1.03/World (2010) H/A |

## References

1. Westhoek H et al (2014) Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Glob Environ Change 26:196–205
2. Kuepper B, Riemersma M. European soy monitor—Insights on the European supply chain and the use of responsible and deforestation-free soy in 2017. In: European soy monitor, Sleurink N, Hombergh HVD (eds) 2019, IDH (The Sustainable Trade Initiative) IUCN NL (The Dutch national committee of IUCN—The International Union for the Conservation of Nature). The Netherlands, p 43
3. Commission, E., Report from the Commission to the Council and the European Parliament on the development of plant proteins in the European Union. 2018, European Commission, Brussels, p 16
4. Commission), E.E. Commission publishes EU feed protein balance sheet for 2019/2020. (2020). https://ec.europa.eu/info/news/commission-publishes-eu-feed-protein-balance-sheet-2019-20-2020-jul-01_en. Accessed 19 Nov 2021
5. future', F.f.t. Protein Challenge 2040. (2017). https://www.forumforthefuture.org/protein-challenge. Accessed 6 Dec 2021
6. Commission, E. (2014) EIP-AGRI Focus Group on Protein Crops: Final Report. In: Schreuder R, Visser CD (eds) European Commission, p 49
7. Spinelli J (1980) Unconventional feed ingredients for fish feed. Fish feed technology. Rome, UNDP/FAO, ADCP/REP/80/11, pp 187–214
8. van Huis A, Oonincx DGAB (2017) The environmental sustainability of insects as food and feed. A review. Agron Sustain Dev 37(5):43
9. Halloran A et al (2016) Life cycle assessment of edible insects for food protein: a review. Agron Sustain Dev 36(4):57
10. Čičková H et al (2015) The use of fly larvae for organic waste treatment. Waste Manag 35:68–80
11. Dreyer M et al (2021) Environmental life cycle assessment of yellow mealworm (Tenebrio molitor) production for human consumption in Austria—a comparison of mealworm and broiler as protein source. Int J Life Cycle Assess 26(11):2232–2247
12. Pinotti L et al (2019) Review: Insects and former foodstuffs for upgrading food waste biomasses/streams to feed ingredients for farm animals. Animal 13(7):1365–1375
13. Pinotti L et al (2021) Recycling food leftovers in feed as opportunity to increase the sustainability of livestock production. J Clean Prod 294:126290
14. Roffeis M et al (2015) Pig manure treatment with housefly (*Musca domestica*) rearing—an environmental life cycle assessment. J Insects Food Feed 1(3):195–214
15. Tschirner M, Simon A (2015) Influence of different growing substrates and processing on the nutrient composition of black soldier fly larvae destined for animal feed. J Insects Food Feed 1(4):249–259
16. Oonincx DGAB et al (2015) Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. PLoS ONE 10(12):e0144601
17. Finnveden G et al (2009) Recent developments in Life Cycle Assessment. J Environ Manag 91(1):1–21
18. ISO (2006) ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework. International Organization for Standardization, Geneva
19. ISO (2006) ISO 14044:2006 Environmental management—Life cycle assessment—Requirements and guidelines. Brussels
20. Thévenot A et al (2018) Mealworm meal for animal feed: environmental assessment and sensitivity analysis to guide future prospects. J Clean Prod 170:1260–1267
21. Smetana S et al (2016) Sustainability of insect use for feed and food: Life Cycle Assessment perspective. J Clean Prod 137:741–751
22. EC (2009) REGULATION (EC) No 1069/2009 OFTHE EUROPEAN PARLIAMENT ANDOFTHE COUNCIL of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No 1774/2002 (Animal by-products Regulation), T.E.P.a.t. Council, Editor. The European Parliament and the Council, p 33
23. Wernet G et al (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21(9):1218–1230
24. FEFAC (2018) PEFCR Feed for Food Producing Animals. First public version (v4.1). https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm. European Feed Manufacturer's Federation
25. Oonincx DGAB, de Boer IJM (2012) Environmental impact of the production of mealworms as a protein source for humans—a life cycle assessment. PLoS ONE 7(12):e51145
26. Canals LMI et al (2011) Approaches for addressing life cycle assessment data gaps for bio-based products. J Ind Ecol 15(5):707–725
27. European C et al (2016) Guide for interpreting life cycle assessment result. Publications Office
28. Ciroth A (2021) Data quality in life cycle inventories. In: Ciroth A, Arvidsson R (eds) Life cycle inventory analysis: methods and data. Springer, Cham, pp 97–122
29. Winther U et al (2020) Greenhouse gas emissions of Norwegian seafood products in 2017. SINTEF Ocean AS
30. Wikipedia. Soybean. 2021 6 March 2021. https://en.wikipedia.org/wiki/Soybean. Accessed 12 March 2021
31. Wikipedia. Wheat flour. 2021 1 February 2021. https://en.wikipedia.org/wiki/Wheat_flour. Accessed 12 March 2021
32. Lurdes MD et al (1998) Lipid and protein changes during the ensilage of blue whiting (Micromesistius poutassou Risso) by acid and biological methods. Food Chem 63(1):97–102
33. Crépon K et al (2010) Nutritional value of faba bean (*Vicia faba* L.) seeds for feed and food. Field Crops Res 115(3):329–339
34. European Commission Joint Research Centre, ILCD handbook (2010) International Reference Life Cycle Data System. General guide for Life Cycle Assessment. Detailed guidance. Joint Research Centre—Institute for Environment and Sustainability, Luxembourg
35. FAO (2003) World agriculture: towards 2015/2030. An FAO perspective. FAO
36. FAO (2013) Food wastage footprint. Impacts on natural resources. Summary report. FAO—Office of Assistant Director-General (Natural Resources Management and Environment Department), p 63

37. European Commission (2017) D.A. EU protein strategy—EU protein balance sheet 2016/17. https://www.fediol.eu/web/eu%20protein%20strategy/1011306087/list1187970179/f1.html. Accessed 9 April 2021
38. Lyng K-A et al (2015) The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. Int J Life Cycle Assess 20(4):490–502
39. Oonincx DGAB et al (2011) An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. PLoS ONE 5(12):e14445
40. Janssen RH et al (2017) Nitrogen-to-protein conversion factors for three edible insects: *Tenebrio molitor*, *Alphitobius diaperinus*, and *Hermetia illucens*. J Agric Food Chem 65(11):2275–2278
41. Pinotti L, Ottoboni M (2021) Substrate as insect feed for biomass production. J Insects Food Feed 7(5):12
42. Flyingfeed (2019) Flying feed—Norway. https://www.flyingfeedfredrikstad.com/. Accessed Nov 2019
43. Retura (2019) Larver er løsningen (translated from Norwegian: worms is the solution). https://retura.no/blog/larver-er-losningen/. Accessed Nov 2019
44. FredrikstadBlad (2019) Investerer millionbeløp i nytt Fredrikstad-selskap—skal produsere larver i stor skala til bruk i fiskefôr. FredrikstadBlad 2019. https://www.f-b.no/nyheter/oppdrettsnaring/david-tehrani/investerer-millionbelop-i-nytt-fredrikstad-selskap-skal-produsere-larver-i-stor-skala-til-bruk-i-fiskef-r/s/5-59-1565012?access=granted. Accessed Nov 2019
45. D2-DagensNæringsliv (2019) Kunsten å dyrke insekter (translated from Norwegian: The art of breeding insects). https://www.dn.no/d2/smak/bugging-denmark/jakob-rukov/myldregard/kunsten-a-dyrke-insekter/2-1-9371. Accessed Nov 2019
46. Protix (2019) Food in balance with nature. https://protix.eu/#. Accessed Nov 2019
47. Agroloop (2019) Closing the loop on sustainable Feed and fertilizer industry. http://www.agroloop.eu/. Accessed Nov 2019
48. Modahl IS et al (2016) Biogassproduksjon fra matavfall og møkk fra ku, gris og fjørfe. Status 2016 (fase IV) for miljønytte for den norske biogassmodellen BioValueChain. Ostfold Research
49. IPCC (2013) Climate Change 2013: The Physical Science Basis, IPCC Working Group, Contribution to AR5 (the Fifth Assessment Report). http://www.climatechange2013.org/
50. UNEP/SETAC (2016) Global guidance for life cycle impact assessment indicators, vol 1, Frischknecht R, Jolliet O (eds). United Nations Environment Programme, Paris
51. Fazio S et al (2018) Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method. New models and differences with ILCD. http://publications.jrc.ec.europa.eu/repository/handle/JRC109369. European Commission, JRC: Ispra
52. Seppälä J et al (2006) Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an Impact Category Indicator (14 pp). Int J Life Cycle Assess 11(6):403–416
53. Posch M et al (2008) The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int J Life Cycle Assess 13(6):477
54. Bos U et al (2016) LANCA—Characterization Factors for Life Cycle Impact Assessment. Version 2.0. http://publica.fraunhofer.de/documents/N-379310.html. Fraunhofer Verlag, Stuttgart
55. Thévenot A (2019) On water use for rearing mealworms (personal communication)