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Sustainable use of *Hermetia illucens* insect biomass for feed and food: Attributional and consequential life cycle assessment

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ABSTRACT

The lack of protein sources in several parts of the world is triggering the search for locally produced and sustainable alternatives. Insect production is recognized as a potential solution. This study is a life cycle assessment (LCA) of food industry side streams transformation via *Hermetia illucens* into intermediate products applicable for feed and food purposes. It relies on attributional modelling for the estimation of the most impacting stages of insect production and on consequential modelling for the estimation of potential benefits or risks for the agri-food system. The consequential LCA included effects on the market, associated with upstream increase in feed (increase in commercial feed production) or downstream availability of insect product (substitution of fertilizer, protein concentrate for feed or chicken meat). Attributional and consequential LCAs are followed by sensitivity analyses, which identify the most promising directions towards sustainable insect production and estimate the magnitude of impact reductions if those directions are pursued by the industry. Analyses of the existing pilot process largely correspond with other findings in the literature, indicating fresh insect biomass is almost twice more sustainable than fresh chicken meat. Produced at pilot scale, protein concentrate (insect meal) while being competitive against animal-derived (whey, egg protein, fishmeal) and microalgae, has higher environmental impacts than plant-based meals. Further scenarios illustrate strategies for more sustainable use of environmental resources providing guidance for producers and funding agencies to direct the industry to an impact profile that is lower, than many existing protein sources.

1. Introduction

Insects are recognized as a potential solution for the global problems associated with the lack of protein sources for feed and food due to the increasing world population (van Huis et al., 2013). In recent years, a significant increase is observed in the number of studies and commercial developments associated with the application of insect production in relation to recycling, reutilization and reuse of side-streams and waste biomass from agri-food systems. Despite multiple literature sources on the questions of economic feasibility, social acceptance and environmental impact, many open questions are left for the researchers to explore. Among the critical issues are the efficiency of insects as biomass transformers, safety of such a technology and sustainability of insect application for food and feed purposes.

Available literature indicate the promising potential of *Hermetia illucens* the black soldier fly (BSF) use as a substitute for commercially available feed ingredients (Allegretti et al., 2018; Magalhães et al., 2017; Nyakeri et al., 2017; Renna et al., 2017; Rumpold and Schlüter, 2014). Many studies highlight the possibility to replace increasingly expensive protein sources of feed (fish meal and soybean meal) (Liu et al., 2017; Loponte et al., 2017), specifically feasible due the potential of agri-food waste, municipal waste (Diener et al., 2011) or manure use for insect feeding (ur Rehman et al., 2017). Salomone with coauthors also notes the potential of technologies based on *Hermetia* as more environmentally preferable alternative for the treatment of biowastes (Salomone et al., 2017). While another group of authors led by Allegretti highlights a better exergy to energy transformation compared to soymeal when renewability and digestibility was taken into account (Allegretti et al., 2018).

H. illucens is noted for having high levels of protein (37–63% dry matter base) and fats (up to 49%), and several macro- and micronutrients important for animal development and human nutrition. It is also indicated in literature that insect biomass can have specific antimicrobial properties (Elhag et al., 2017; Makkar et al., 2014), which has

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a potential of being applicable in feed industry as an additive to feed. *H.illucens* is also highly tolerant to toxins like aflatoxin B1 (Bosch et al., 2017; Camenzuli et al., 2018), mycotoxins and pesticides (Purschke et al., 2017). The monitoring of heavy metals concentrations should be recommended (Purschke et al., 2017; van der Fels-Klerx et al., 2016). It is especially relevant taking into account fluctuations in life stages (Barragan-Fonseca et al., 2017; Liu et al., 2017) and diet (Barragan-Fonseca et al., 2017; Cammack and Tomberlin, 2017; Spranghers et al., 2017). Downstream processing (insect biomass processing) is becoming even more important if it can assure the safety of biomass used for bio-waste treatment. The guidelines for the application of *H. illucens* for waste treatment indicate that a small-scale enterprise can treat 60 kg of bio-waste with 40.000 larvae on 1 m^2 over a 12-day period (Dortmans et al., 2017). However, the safety of insect biomass grown on bio-waste should be assured before it can be used for food and feed purposes.

Insects are considered as less environmentally impacting source of proteins than meat products. However, in certain cases their environmental impact might be in the range of impacts similar to chicken and pork products, e.g. nitrous oxide emissions (Oonincx, 2017) and land use (Smetana et al., 2016). However, the level of impact highly depends on the diet, production system and species, as some of them lead to the increased emissions compared to others (Oonincx, 2017).

Insects, containing high amounts of proteins, are also perceived as a potential substitute for meat (Smetana et al., 2016, 2015; van Huis et al., 2013). While research literature covers a wide range of insect species and their application for food (van Huis, 2017), *H. illucens* remains out of the research range (Wang and Shelomi, 2017). Despite a vast coverage of insect related topics in literature, the existing research still lacks industrial scale information. Industrial scale is important for reliable comparison with traditional protein sources, and industrial guidelines development. Most of the analyses of economic feasibility and environmental impact are performed for small pilot or small industrial scale of production with rate of 0.02–1 ton of insect biomass processed (dry weight basis) per day (Halloran et al., 2017; Salomone et al., 2017; Thévenot et al., 2018). Even though such assessments are valuable for the determination of environmental hot-spots of insect production they do not represent the scale of industrial potential and, therefore, cannot be referred for economic and environmental impact relevance fur future scenarios modelling. Moreover, most of the studies are based on partial and aggregated data, and do not rely on a consequential LCA approach, which has a potential to identify market system changes of new technologies and products (Larrea-Gallegos et al., 2018; van Zanten et al., 2018).

The goal of this study is the assessment of the determinants of the environmental impacts of insect based intermediate products (usable for feed and food) and to provide guidance on how the industry should move forward to exploit the potential of insects to minimize its environmental impact with specific attention on the potential use of non-utilized biomass from food and feed industries. This study relies on a systemized multi-season dataset of *H. illucens* production and processing from a pilot plant producing above average volumes. These data are analyzed by applying attributional (identification of the optimal production and allocation between products) and consequential life cycle assessment approaches for the definition of more sustainable options. The outcomes of the study indicate the most promising scenarios for sustainable *H. illucens* production for food and feed producers, policy makers and scientists.

2. Methods and materials

2.1. Life cycle assessment

2.1.1. Goal and scope of the study

This study consisted of two parts. First, LCA analyses of historical production data from a pilot plant were performed for understanding the environmental dynamics of *H. illucens* production. In the second part sensitivity analysis of industrial progress was used to indicate where improvements could be made. All analyses were performed with respect to *H. illucens*; the black soldier fly (BSF).

The study included two types of LCA: (1) the analysis of environmental impact of production stages of insect-based products and its comparison to benchmarks (traditional feed and food intermediates); (2) identification of environmental consequences of production and consumption choices towards insect-based feed and food. The results provided clarification on the environmental hot-spots of insect production (attributional approach) and estimation of system consequential changes due to the change of diet of *H. illucens*. System changes included application of side-streams from processing industry and organic waste streams and introduction of insects as an alternative source of proteins for feed and food purposes.

The insect industry is on the verge of transitioning from pilot scale to industrial scale production. Producers at the pilot scale have focused on stable, safe production to demonstrate the potential of their production process. Consequentially, the full potential for environmental impact reduction from insects still lies ahead. Improvements will come from two sources: (1) efficiency improvements informed by pilot plant operations that producers will realize in their next generation facilities; and (2) shifts in inputs as the industry extends operations to incorporate a wider range of feed and energy sources. Building upon the framework of production dynamics developed in the LCA part of the paper, several sensitivity analyses exploring the impact reductions achievable by these two sources of improvement were performed. These analyses estimated the magnitude and highlight the most promising directions for the industry to realize the upcycling potential of insects.

2.1.2. Type of LCA

The LCA study consisted of four main parts: (1) modelling and analysis of *H. illucens* production and processing with available industrial data; (2) attributional LCA (A-LCA) modelling with allocation of impact to by-products and hotspots identification in comparison to benchmark products; (3) consequential LCA (C-LCA) modelling for the scenarios of feed and meat replacement on the market; and (4) sensitivity analysis and identification of more sustainable scenarios of *H. illucens* production.

The assessment followed the standard LCA approach (ISO 14040, 2006; ISO 14044, 2006) and used professional SimaPro v8.2.0.0 software (PRé Consultants B.V., Amsterfoort, The Netherlands) and adapted ecoinvent 3.1 datasets (ecoinvent, Zurich, Switzerland) for background data (electricity and water supply, heat generation, etc.) (Wernet et al., 2016). The study also relied on integrative methodology for life cycle impact assessment: IMPACT2002+ (Jolliet et al., 2003) for most impact categories. The main reason for the selection of the methodology was its ability to provide analysis for mid-point and end-point categories, but also indicate integrated single scores. At the time of assessment, application of IMPACT2002+ (Jolliet et al., 2003) allowed to generate results with low uncertainty level and a recognized approach for end-point results integration. Application of IMPACT 2002+ midpoint assessment methodology (IMPACT World + Midpoint V0.04 for Water footprint after (Boulay et al., 2011)) allowed the indication of results for 15 impact categories. Further results for the impacts were checked for uncertainty (Monte Carlo simulation analysis with 1000 runs performed for mid-point and end-point categories) and integrated for the single score representation (IMPACT 2002+). This way the limitations and uncertainties of both methodologies were acknowledged. Moreover, the influence of the methodologies on the results were tested with ReCiPe midpoint (E) Europe and endpoint methodology (Goedkoop et al., 2013) as a part of sensitivity analysis (see part 3.1).

The A-LCA required the allocation of environmental impact between co-products at the stages of feed production, *H. illucens* growing and harvesting. Economic allocation was applied unless otherwise mentioned. The main allocation factors based on the price of the final products followed the ratios of 3.08:1 fresh insects to fertilizer and 4:1 insect meal to fat with further adjustment according to the relative weight of the product (according to the data from Protix, Dongen, The Netherlands). Waste treatment impacts were allocated to the products accordingly or avoided in relevant cases of C-LCA.

The C-LCA followed established practices (Ekvall and Weidema, 2004; Weidema, 2000; Weidema et al., 1999) to define the decisions between scenarios for: (1) application of protein-rich side-streams of food processing for *H. illucens* diets (with increased demand for other protein feed sources); (2) potential reactions of the market on the increased production of insect meal as a source of feed and food proteins. Multifunctionality was dealt with by the substitution method and only marginal suppliers were included within the system boundaries. The identification of marginal suppliers was based on the guidelines for stepwise market-based system delimitation (Weidema, 2003), however, due to the lack of information for the future progress of insect-based products on the market, it was assumed that the average market producer of relevant products (feed for insects and insect products analogues) would be affected. Foreground and background system modelling were performed using the consequential approach described in the guidelines of ecoinvent (Weidema et al., 2013).

2.1.3. Functional unit

In order to provide a reliable and "fair" comparison of insect derived products for feed and food, a proper indication of insect biomass functions was required. This approach led to the setting of a proper functional unit (FU), system boundaries and assurance of data quality. The analyzed production and processing facility (Protix, Dongen, The Netherlands) is a multiproduct enterprise. Therefore, it was analyzed with a few FUs in the A-LCA, which would reflect the main products and account for the possible results misinterpretations. A-LCA related FUs included: 1 kg of dried and pelletized organic fertilizer (FU1); 1 kg of fresh BSF biomass (puree) used as a component for pet food production (FU2); 1 kg of protein concentrated meal used as feed ingredient (and potentially for food) (FU3); and 1 kg of BSF fat used as feed additive for pork production (FU4). C-LCA modelling was performed on the basis of a single product (fresh *H. illucens* biomass or protein concentrate meal). It included increased demand on the market for three main scenarios: (1) market demand increase for fresh BSF biomass as a substitute for fresh chicken meat; (2) for BSF protein concentrate as a substitute for soybean meal and for fishmeal (3). This way all the functions of BSF production could be accounted and compared to the benchmark products either through comparison of impact results or via benchmark substitution included in modelling.

Additional assessment was performed for the comparison of *H. illucens* products to benchmarks on a dry matter basis. First the dry matter (DM) impact of each product was calculated as relation of environmental impact to DM. Comparing on a dry matter basis allowed for a clearer assessment of impacts, since some products, such as chicken and fresh *H. illucens* contain more water than whey concentrate and insect meal. The dry matter of the products contains the nutrients and is of primary interest for feed and food development. Then, the percentage difference between the dry impacts of a product and *H. illucens* meal was calculated as (DM Impact-DM Impact HM)/(DM Impact HM)X100. Then it was further normalized to the percent difference from the dry matter (DM) of *H. illucens* meal (HM) allows for a straightforward relative comparison across the impact types.

2.1.4. System boundaries

Most of the insect production schemes in Europe fall within a conceptual scheme, similar to animal production: feeding, growing, processing, distributing and consuming. This study followed the general concept of insect production and processing (Smetana et al., 2016), but also relied on more detailed dataset on the production and processing of *H. illucens* (Fig. 1). The studied system considered the scope "from cradle to gate" and included production of raw materials (feed for *H. illucens*), feed processing and storage, cycle of *H. illucens* development (egg production, larvae hatching, growing, larvae harvesting), and processing of outputs into a few products: organic fertilizer, fresh puree, protein concentrate and fat. Further development for feed and food was not considered.

2.2. Scenarios for C-LCA

Two main assumptions were used for the modelling of C-LCA scenarios: (1) the increase of *H. illucens* production, with diet based on side-streams from alcohol and beer production, will trigger the increase in the need to produce other commercial sources of feed for other animals (cattle, pigs and poultry), as currently available side-streams are used as a feed for animals (communication to feed experts); (2) increased production of BSF (for food or feed purposes) will generate organic fertilizer (85.5% of organic matter, dry matter basis), fresh BSF puree (moisture content 70%, protein content 17% and fat content 10%) and BSF protein concentrate (56.3% of proteins, 13.7% of fats, ileal digestibility 89.4%), thus reducing the demand for analogous products on the market (organic fertilizer, chicken meat, feed protein ingredients). It might be argued that fresh *Hermetia* puree is not completely comparable to fresh chicken meat due to some variations in sensory and physical properties, currently it is the closest comparable product in terms of nutritional properties and can potentially substitute chicken meat in food and pet food. Sensitivity scenarios considered the impact from the use of organic residuals unsuitable for feed or human food as feed for insects with avoided need for treatment (see point 2.6). Such assumptions are based on the identification of suppliers as marginal. The performed C-LCA should be treated as indicative rather than precise, but useful for the identification of potential impacts on the food production and consumption system in the future.

2.3. Data sources and uncertainties

The LCA model of *H. illucens* production relied on the production scale data, which is one order higher than those available in literature. Therefore, a dataset covering nineteen-month period (2015–2017) of *H. illucens* production and processing with measured variables of water use, feed inputs, electricity and heat consumption, production yields from an industrial producer (Protix, Dongen, The Netherlands), combining more than one thousand data points, was used for the identification of input and output parameters of industrial production (Table 5A). The data for the upstream production processes (generation of side-streams) were adapted from Agri-footprint database (Blonk Consultants, Gouda, The Netherlands), while most of the processes of water, energy and heat supply were based on European datasets of ecoinvent 3.1 database (ecoinvent, Zurich, Switzerland) (Wernet et al., 2016) (Table 4A). The data for the comparative benchmarks (protein concentrates, fertilizers, fresh biomass) were acquired from recent literature sources (see part 3.1).

In order to identify the potential uncertainties in data used for model construction we applied Monte Carlo simulations with 1000 runs using SimaPro v8.2.0.0 (PRé Consultants B.V., Amsterfoort, The Netherlands). Following this approach, we identified the results with low uncertainties levels and used only these to draw conclusions.

2.4. Assumptions

Despite the application of industrial data for the LCA model construction, the study still required some assumptions related to the attributional and consequential modelling approaches. For the allocation of the impact of insect diet components (by-products of food industry) we used economic allocation similar to the approach of the Agri-footprint database (Blonk Consultants, Gouda, The Netherlands). The prices for the products (and accordingly economic allocation factors) were provided by the industrial producer (Protix, Dongen, The Netherlands)

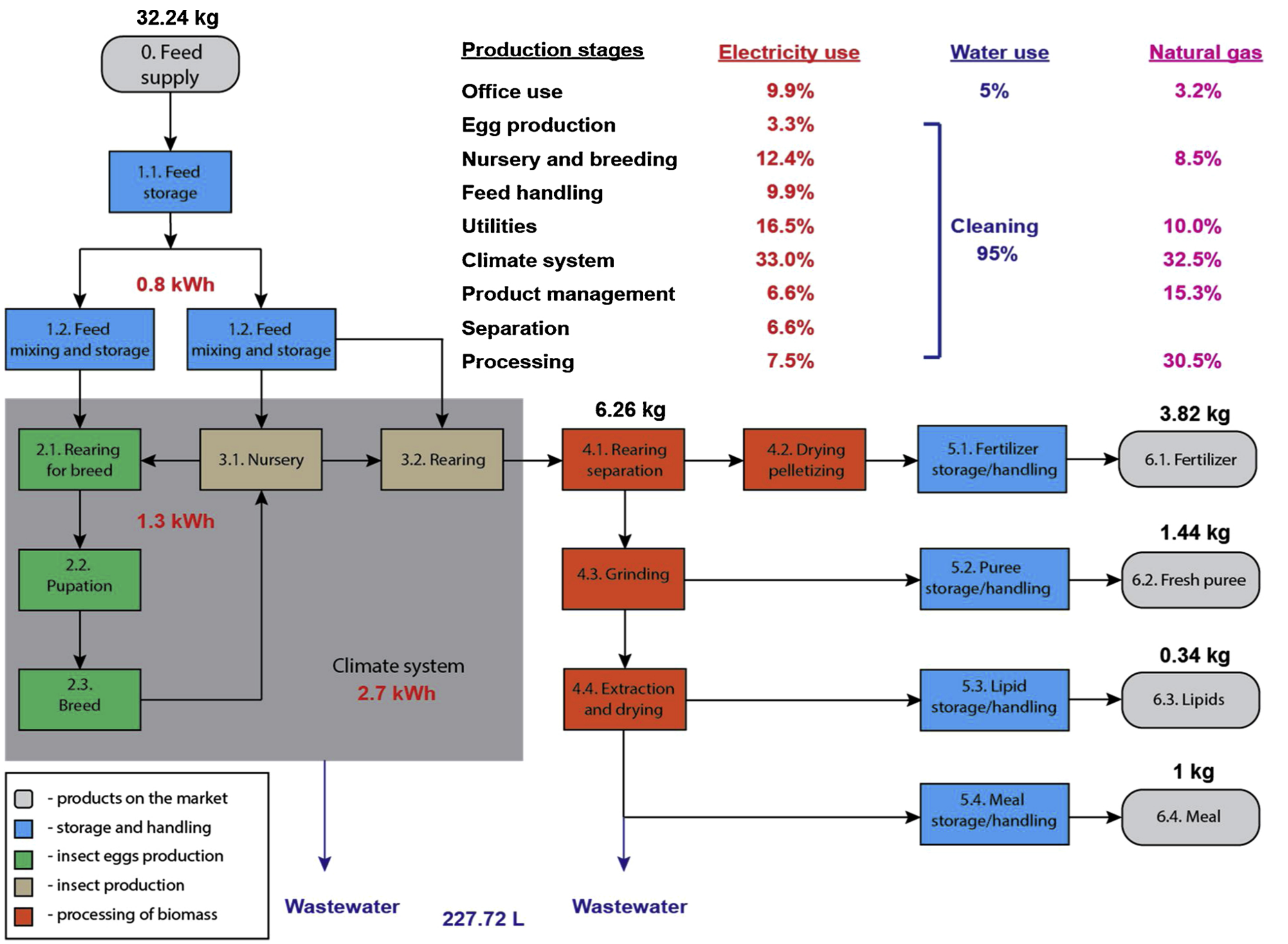

Fig. 1. System boundaries of the study (attributional modelling) including inputs distribution and relative mass flows.

as well as modelling was performed with the data from one industrial source, and, therefore, should not be directly extrapolated to other industrial partners dealing with different production systems.

The C-LCA included modelling of production with substituted products. *H. illucens* production, assessed in the study, relied on food processing side-streams (wheat starch slurry, wheat middlings and condensed distilled solubles), which were assumed to be used as feed for animals (pigs). Therefore, an increase in demand for *H. illucens* feed, resulted in response from marginal market (increase of commercial feed production). Thus, C-LCA modelling included increased demand for feed ingredients (soybean meal). At the same time, production of fresh insect biomass and organic fertilizer were assumed to substitute similar products (fresh chicken meat and organic fertilizer) on the market, avoiding the need for their production. Further processing of fresh insect biomass resulted in formulation of defatted *H. illucens* meal which can potentially substitute soybean meal or fishmeal (Kroeckel et al., 2012; Maurer et al., 2016; Sánchez-Muros et al., 2014). The substitution of the products was performed according to the protein content or organic matter content (fertilizer).

2.5. Sensitivity analyses

Sensitivity analyses to assess the potential magnitude of environmental impact reduction in the insect industry in the short-term were based on direct assessments of next-generation growing hardware. Mid and long-term analyses assumed changes to key inputs that are already being explored by the industry as logical steps for reducing environmental footprint in the production process, for example as automated production units (Hu et al., 2010; Kok, 1983). Insect FUs re-evaluated in the different sensitivity analyses will be denoted by "_ST", "_MT" and "_LT" for short-, mid- and long-term scenarios, respectively.

Short-term (ST) scenarios included aggregated improvements of approximately 25% each in feed and energy. Derived impacts were determined with direct previous trials and should achieved due to improved feed conversion, application of adapted hardware of higher scale and more controlled use of resources by the end of 2019 in a new facility being constructed by Protix in the Netherlands.

H. illucens is a promising biomass transformer capable of consuming feed streams that are not suitable for other livestock (Wang and Shelomi, 2017). Today insect producers already partially rely on inclusion of at least one type of side (waste) stream into insect production. Next generation facilities that can maintain safe and stable production will increasingly turn towards diets based on streams unsuitable for other animals and potentially streams that present technical challenges; these can be referred to as non-utilized side-streams. Furthermore, improvements in insect genetics and selection of appropriate side-streams can lead to the reliance on the non-utilized side-stream feeds in mid-term future (MT) within next 5–7 years.

The application of non-utilized side-stream for feed reduces direct impacts of insect production and has an impact on the larger food production system. To account for both dynamics, A-LCA and C-LCA sensitivity analyses are performed. In the C-LCA analysis, two scenarios were investigated. In one, composting treatment of the insect feed was avoided, while in the second, anaerobic digestion was unnecessary.

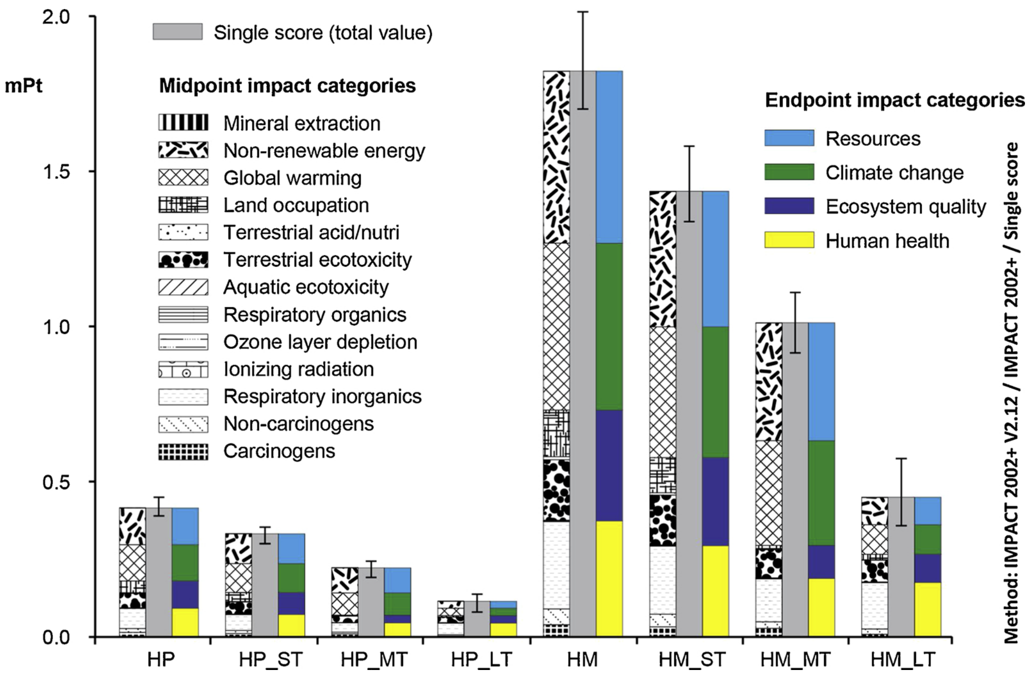

Fig. 2. Environmental impact of insect products (HP – *H. illucens* puree scenarios (fresh insect production); ST –25% feed conversion efficiency and energy use; MT –application of non-utilized side-streams; LT –energy supplied from renewable sources; HM – *H. illucens* meal (defatted protein concentrate) scenarios; Methodology IMPACT2002+, FU 1 kg of product, error bars – standard deviation; Pt – ecopoints, relative measure of environmental impacts with 1 kPt equal to the annual impacts of one European person).

Energy consumption is a major source of environmental impact for insect production and processing. A logical way to reduce this impact is to rely on renewable energy sources. That is why a transition to alternative energy sources was foreseen as a feasible option in a long-term (about 10 years) perspective (LT) due to the need of a considerable investments required. In this sensitivity analysis, photovoltaic energy production was assumed as input. Long-term scenarios included non-utilized side-stream for feed and the short-term efficiency improvements. Since the primary C-LCA effects of this scenario were realized using non-utilized side-stream for feed, only an A-LCA analysis is conducted for long-term scenarios.

3. Results and discussion

3.1. Identification of insect production and processing impact with A-LCA

Production of *H. illucens* was based on the side-streams diet. The diet consisted of commercially available side-streams from the food industry (milling, alcohol production and brewery). Therefore, modelling of such inputs required the allocation of *H. illucens* feed (side-streams were determined as by-products of the food industry as they are usually sold as feed for farm animals). Allocating the food side-streams as co-products identified them as valuable biomass sources rather than as wastes.

In Fig. 2, A-LCA impact results are presented for *Hermetia* puree (HP) and *Hermetia* protein meal (HM). Additionally, the sensitivity analysis for short-term (ST), mid-term (MT) and long-term (LT) were computed for HP and HM. The greatest sources of impacts in all categories were feed production and energy use. For HP these made up 43% and 36.5%, respectively. This ratio, whereby feed production had a slightly higher impact than energy, was observed for the other products as well, except for HM, where 55% of all environmental impacts were associated with production of electricity used along the production chain and 38% of impacts was allocated to insect feed production. This difference was because of the energy requirements needed in the additional processing steps to transform HP to HM. Insect fertilizer (IF) and *Hermetia* fat (HF) were co-products of HP and HM production. The impacts allocated to IF and HF were lower than those of main products (Table 1A).

The highest relative impacts for all the products was observed in the categories of Global warming and Non-renewable energy consumption (around 50% of impacts). Respiratory inorganics, terrestrial ecotoxicity and land occupation also had considerable impacts at 40%. High impacts in the categories confirmed the conclusion on the highest impact of feed and growing of *H. illucens* (energy use). Overall impacts of insect products varied in the scope of 0.33 mPt for insect fertilizer to 1.82 mPt for *Hermetia* meal (Pt – ecopoints, relative measure of environmental impacts with 1 kPt equal to the annual impacts of one European person) (Fig. 2). The results demonstrated that fresh *H. illucens* biomass, even produced at a pilot scale, was more environmentally beneficial than chicken meat. Moreover, the A-LCA indicated that *Hermetia* meal produced at pilot industrial scale could be also competitive to chicken meat (overall chicken impact is ˜2 mPt).

The general conclusions for the baseline impacts were in line with results in the literature (Smetana et al., 2016, 2015). However, the level of detail and certainty was higher due to the quality of the data and more precise modelling of the production process. This detailed framework enabled the sensitivity analyses for short, medium and long-term developments that are foreseeable in the progression of the insect industry. Considering HP and HM, the step to next phase technology can be expected to reduce the impact of production by approximately 25% (based on previous industrial scale equipment testing). Further improvements in production efficiency can be expected at later phases, such as improved animal efficiency due to genetic improvement, but these effects were difficult to estimate and account for in a sensitivity analysis. Likewise, the use of non-utilized side-streams for feed that are unsuitable for conventional livestock can reduce the direct impact of BSF production again by a quarter. Finally, the use of renewables to power production again reduce the impacts by about 25%. However, while the short and medium-term improvements tended to reduce the various impacts proportionally, the switch to renewables disproportionally obtained its positive effect by reducing the impacts from non-renewables and global warming. It should be mentioned that other sources of proteins are likely to achieve certain benefits from switching to alternative energy sources. In this case the comparison of LT scenarios to benchmark alternatives might be less robust in this case.

The sustainability of insect production is typically cited as one of

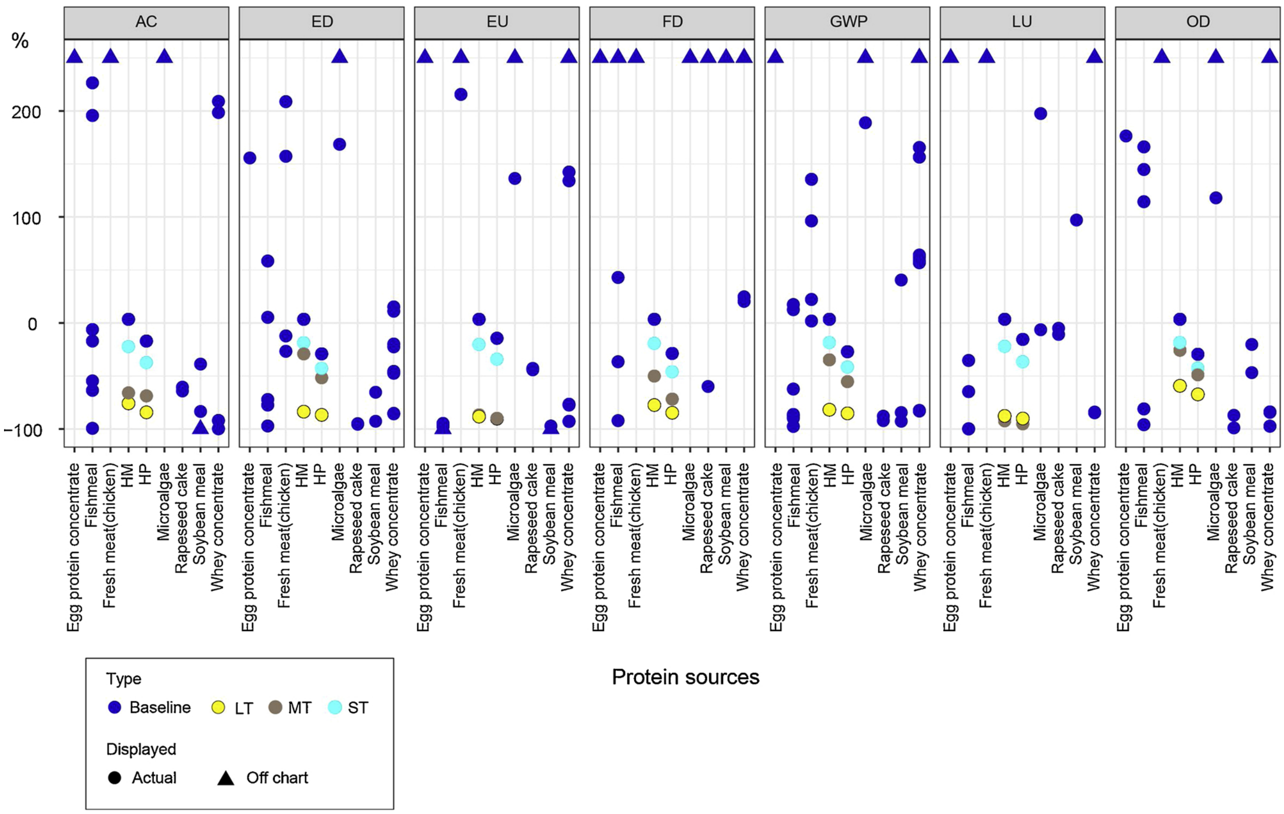

Fig. 3. Environmental impacts of different sources of proteins (dry matter basis) weighted against HM, GWP – global warming potential; OD – ozone depletion; AC – acidification; EU – eutrophication; ED – energy demand; FD – freshwater depletion; LU – land use, relative impacts are censored at -100% and 250% to maintain the readability of the plot and as triangles at these limiting values, references for the analysis of environmental impacts are in Table A.2.

their advantageous properties. The impact of HM and HP was compared to other protein sources based on values found in the literature. In Fig. 3, various types of environmental impact are displayed relative to the baseline value for HM on a dry matter basis (exact inputs are in Table 2A).

Broadly, insect proteins were compared against other sources, which can be classified as animal and non-animal sources. Animal-based protein sources used for human nutrition almost universally displayed higher average values across the impact types than BSF proteins. Fishmeal is an important animal-based protein source used in feeds and pet food. Insect products are often portrayed as a solution to the unsustainable overfishing behind fishmeal (van Huis, 2017). Fishmeal production is markedly different from land-based protein production as its production does not require additional inputs of land or water, and energy is primarily from nature. On the other hand, it is noted for its damage to biodiversity and ecosystems. This makes it difficult to compare with land-based proteins. Baseline pilot scale production of insect proteins had impacts that were around the middle or high estimates of fishmeal's impact, depending on the type of impact. However, the sensitivity analyses indicated that insect proteins showed lower impacts than fishmeal over most of the impact types. This was because the combination of efficiency improvements, reliance on sustainable feed and reduced application of non-renewable energy captured most of the positive benefits of fishmeal production without its environmental consequences.

Plant-based proteins are among the most sustainable. It is only in the mid and long term that insect proteins could be environmentally competitive across most of the impact types, but again a switch to sustainable feed and renewable energy is vital to gain the beneficial position comparing to plant-based proteins. There were two exceptions to this pattern: fresh water depletion and land use. Insect production, even at the baseline showed lower impact estimates in these categories than soybeans and with the efficiency gains in next-generation production it became competitive against rapeseed cake. Therefore, while the outlook may be that it will require mid to long term improvements for BSF proteins to achieve impacts as low as plant-based sources across many types of impacts, in locations where water and land are scarce, or habitat destruction for agriculture is an issue, BSF production may already be a preferable protein source.

Microalgae is another emerging source of proteins, which can provide beneficial products for human nutrition. The impact estimates of these nascent protein sources are all off the high end of the chart. However, due to lacking technology readiness in many stages of the value chain and missing economy of scale for broad applications short, mid and long-term improvements need to be taken into account as well.

A sensitivity analysis testing the dependency of results and conclusions on changes to assumptions and methodological choices was performed for A-LCA results with the alternative life cycle impact assessment methodology (ReCiPe). It indicated that the relative impacts of products had similar distribution to those presented (Fig. 2).

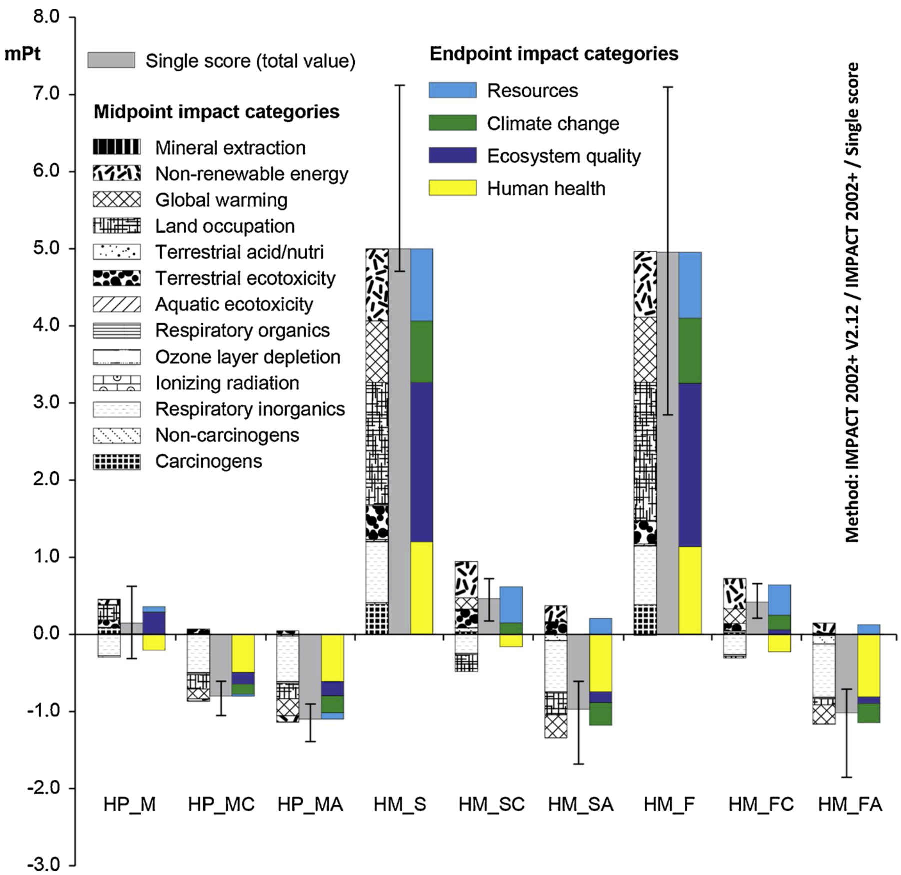

Fig. 4. Environmental impact of insect products with accounting of consequences of market changes (HP_M – *H. illucens* puree (fresh insect production) with chicken production (live weight) substituted; C –with avoided need to compost non-utilized side-streams used as feed for insects; A –with avoided need to treat non-utilized side-streams used as feed for insects (anaerobic digestion); HM_S – *H. illucens* meal (defatted protein concentrate) with soybean meal production substituted; HM_F – *H. illucens* meal (defatted protein concentrate) with fishmeal production substituted; Methodology IMPACT2002+, FU: increase in market demand for 1 kg of product with the substitution of alternative benchmark product, error bars – standard deviation; Pt – ecopoints, relative measure of environmental impact with 1 kPt equal to the annual impact of one European person).

Moreover, the endpoint single score impact of most insect products (0.16 Pt/kg of fertilizer, 0.21 Pt/kg of fresh puree, 1.01 Pt/kg of *Hermetia* meal) was higher than the impacts of fishmeal: 0.017-0.11 Pt/kg of fishmeal (Fréon et al., 2017), which corresponds to the comparative results (Table 2A).

3.2. Consequences of increased market demand of insect derived products

The C-LCA included the potential changes to the feed and food markets as a reaction to the changes caused by insect production. In addition to the baseline case, two sensitivity analyses were performed for HP and HM involving a transition to non-utilized side-streams as feed. Fig. 4 displays the results of these analyses (Table 3A provides the midpoint categories impact results). It was assumed that HP substituted chicken meat on the market (HP_M), while HM avoided soy meal (HM_S) and fishmeal (HM_F) since they are both common protein sources in feed. *H. illucens* fertilizer caused the avoidance of organic fertilizer production (IF_F).

3.2.1. Results for the base case

In the base case, where side streams that could be used for other livestock are fed to *H. illucens*, the C-LCA approach demonstrated that a change in the feed supply chain to insect production would be associated with demand and supply of high-protein side streams from the food industry (milling, alcohol production and breweries). Currently these side-streams are utilized for feed ingredients. Increased demand for this feed would potentially trigger the increased demand for other high-protein feeds (e.g. soybean meal) to substitute the gap of protein feed for other animals. Moreover, the C-LCA approach distinguishes food production side-streams as single products with substitution of milling and brewery products on the market. This approach resulted in improvement of environmental impact of BSF products.

Further modelling of an increase in market demand for insect products included the need to identify the products substituted on the market. Substitution of organic fertilizer (ecoinvent 3.1) resulted in reduction of environmental impact of *H. illucens* fertilizer production (compared to A-LCA calculated impacts). Moreover, the substitution of organic fertilizer with insect produced alternatives resulted in positive environmental impacts in multiple impact categories. Production of fresh *H. illucens* biomass as a meat substitute similarly resulted in improvement of environmental impact. However, environmental impact was positive only in a few impact categories (Non-carcinogen emissions, Respiratory inorganics, Ionizing radiation, Terrestrial acidification and nitrification, Aquatic acidification and Water use), which had a relatively low contribution in overall impact score (Fig. 4).

3.2.2. The effect of using non-utilized side-streams for feed

Two sensitivity analyses were considered for HP and HM. In the first (denoted with C), it was assumed that non-utilized side-streams were fed to *H. illucens* and that composting of the feed was not necessary. In the second, (denoted with an A), it was assumed that non-utilized side-streams were fed to insects and that anaerobic digestion was avoided. In the case of HP, regardless of the processing assumption, the types of impact nearly all displayed reductions over chicken production. In the case of HM production, switching to waste streams substantially closes the gap between *H. illucens* meal and soy or fishmeal. Composting substitution of non-utilized side-streams used as a feed for HM showed substantial reduction of environmental impact. When anaerobic digestion is avoided HM is expected to demonstrate beneficial environmental impact, which would make it the most environmentally friendly source on the market. It is necessary to indicate that the anaerobic digestion model included production of biogas as a by-product of waste treatment, but the comparison did not include the potential substitution of biogas with natural gas production in case used as feed for insect production. The reductions observed in the sensitivity analyses compared to the base case arise, because the use of feeds, which are unsuitable for other livestock, did not stimulate additional production of those feeds for livestock as current production was directed towards insects. The sensitivity analysis demonstrated that feeding livestock with *H. illucens* meal could become more beneficial (than soymeal or fishmeal) if insects are fed with non-utilized side-streams aimed for composting or anaerobic digestion.

3.3. Uncertainty analysis

The single score impact results (overall environmental impact, see part 3.1) demonstrated that A-LCA had relatively low uncertainties levels (compared to C-LCA, part 3.2). However, different midpoint impact categories were characterized with various standard deviation (STD) levels for 95% of confidence interval. The lowest STD was indicated for Land use (3–4%), Global warming impacts (4–6%) and Respiratory inorganics (7–10%). STD of results for Non-renewable energy use category varied from 14% to 22% and for Water use from 12 to 14% for all the A-LCA scenarios. The highest uncertainty levels of A-LCA were indicated for Terrestrial ecotoxicity: 18–48%.

Environmental impact results with C-LCA were characterized with high ranges of STD (Fig. 4), which reached ranges of results variability from 50 to 150%. Despite a high variability, the overall tendencies towards reduction of environmental impact for fertilizer and fresh biomass and increase of impact for *Hermetia* meal, when these materials are produced at a pilot scale on feed streams remained. At the same time, it indicated the need for the improvement of background data used for C-LCA modelling of insect production. Further modelling of benchmark products with the first-grade data should improve the quality of results. However, the indicative nature of C-LCA results allowed previous identification of trends for application.

3.4. Guidance for the industry

General improvements to production technology efficiency can be expected from the more advanced players in the industry. These are likely to produce sizable gains in the short-term, as they are motivated not only by environmental concerns but also by the cost savings they bring. The shift to these technologies is occurring as pilot plant technologies are refined and specialized machinery is being developed or transferred from other more advanced production processes to insect production. New entries to the industry who are exploring technology options will benefit from reduced impacts by selecting maturing technologies.

The shift to non-utilized side-streams for feed is perhaps the most important for the development of the environmental potential of the insect industry. Both the A-LCA and C-LCA sensitivity analyses indicated that using feeds not suitable for livestock feed or human food will have sizable direct impact reductions and could fundamentally change our feed and food production systems. However, the shift to non-utilized side-streams in feed comes with industry specific challenges. Whereas efficiency improvements in production technology can borrow extensively from developments in other industries, using some non-utilized side-streams for insect feed requires specific development. The results of the analyses showed that industry operators and government support that drives improvements in safety and quality as well as the development of networks for non-utilized side-streams collection not directly usable as insect feed will be rewarded with sizable environmental impact reductions. As this process matures, industry players and communities that can successfully switch to these types of streams are also likely to benefit from lower costs of production and advantages from a circular economy.

Finally, the switch to renewable energy is a key for bringing the global warming impact of insect production below the levels realized by nature-based production systems not so strongly dependent on energy use, such as fishmeal and crops. At the same time, it is unlikely that on-site renewables will be a solution for all insect producers. However, the sensitivity analysis is a useful guidance for industrial producers interested in a holistic approach to managing their environmental impact profile. Moreover, it showed that a government, which supports renewables development, will be able to extend the environmental impact reductions from that technology by supporting insect production with a low global warming footprint. Thus, they would accrue the benefits of insect production, such as low land and water use, without the negative repercussions of intensive high-tech land-based food production.

4. Conclusions

The aim of the current study was the assessment of environmental impacts of insect-based intermediate products (usable for feed and food) with reliance on systemized multi-season dataset of *H. illucens* production and processing. This was done by considering a highly productive pilot plant with insight on future upscaling scenarios applying attributional (identification of the optimal production and allocation between products) and consequential LCA approaches for the definition of more sustainable options.

Attributional LCA of a high productivity pilot industrial scale of *H. illucens* production indicated its lower environmental impacts than similar sources of animal biomass for food. The results of this study showed that current insect production offers the potential for more sustainable protein, fertilizer and lipid production. Fertilizer production, even at the pilot scale was more environmentally favorable compared to conventional organic fertilizer. Insect fats and proteins, if used in human food applications were environmentally preferable to many animal-based food sources, and on some impact types like water and land usage they were favorable to plant based proteins. However, to assure the environmental benefits expected from insects, the industry will need to consciously make additional steps.

Upscaling of insect production (improved efficiency of feed conversion and processing) reduced environmental impact making *H. illucens* biomass competitive to feed protein sources. Further application of non-utilized side-streams or alternative sources of energy for processing will result in a more beneficial source of proteins than most known alternatives. However, the availability of non-utilized side-streams, usable for the insect production is a key factor which would determine the further development of the insect industry. The environmental impact of insect production additionally would depend on substitution of non-utilized biomass treatment, alternative utilization options and their geographic distribution. The consequential LCA indicated that transforming organic residuals into *H. illucens* biomass could result in lower environmental impacts if composting or anaerobic digestion (as a waste treatment technology) is avoided.

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Appendices A. Appendices tables should be under Appendices A heading

Table 1A
Impact results for midpoint categories (A-LCA, IMPACT 2002+, FU 1 kg of product)

Impact category	Unit	IF	HF	HP	HP_ST	HP_MT	HP_LT	HM	HM_ST	HM_MT	HM_LT
Carcinogens	kg C_2H_3Cl eq.	0.014	0.068	0.034	0.027	0.025	0.006	0.099	0.081	0.073	0.025
Non-carcinogens	kg C_2H_3Cl eq.	0.029	0.093	0.032	0.026	0.013	0.011	0.128	0.103	0.053	0.043
Respiratory inorganics	g $PM_{2.5}$ eq.	0.567	2.080	0.658	0.520	0.308	0.381	2.852	2.224	1.406	1.512
Ionizing radiation	Bq C-14 eq.	7.944	39.173	9.311	7.759	6.890	2.621	53.146	41.749	38.400	10.375
Ozone layer depletion	mg CFC-11 eq.	0.068	0.313	0.091	0.074	0.066	0.042	0.430	0.339	0.309	0.169
Respiratory organics	g C_2H_4 eq.	0.143	0.581	0.210	0.165	0.137	0.140	0.811	0.641	0.531	0.554
Aquatic ecotoxicity	ton TEG water	163.292	535.702	0.176	0.157	0.125	0.110	0.733	0.643	0.522	0.430
Terrestrial ecotoxicity	ton TEG soil	79.043	247.422	0.081	0.068	0.036	0.032	0.337	0.278	0.157	0.122
Terrestrial acid./nitri.	kg SO_2 eq.	0.029	0.092	0.030	0.023	0.007	0.005	0.125	0.096	0.031	0.020
Land occupation	m^2org.arable	0.473	1.383	0.477	0.360	0.028	0.056	1.888	1.423	0.143	0.224
Aquatic acidification	kg SO_2 eq.	0.005	0.015	0.005	0.004	0.002	0.001	0.021	0.016	0.007	0.005
Aquatic eutrophication	g PO_4 P-lim	0.196	0.792	0.215	0.188	0.163	0.146	1.076	0.895	0.797	0.574
Global warming	kg CO_2 eq.	0.877	3.872	1.157	0.928	0.712	0.235	5.325	4.174	3.339	0.931
Non-renewable energy	MJ primary	13.010	61.183	17.876	14.447	12.235	3.387	84.178	66.200	57.675	13.356
Mineral extraction	MJ surplus	0.023	0.108	0.028	0.023	0.022	0.043	0.147	0.118	0.113	0.171
Water use*	L deprived	0.005	0.020	0.565	0.453	0.238	0.130	2.770	2.185	1.354	0.610

Note: IF – insect fertilizer (dried and pelletized); HF - *H. illucens* fat; HP – *H. illucens* puree (fresh insect production); HP_ST – HP scenario involving 25% feed transfer and energy use improvements; HP_MT – HP scenario involving 25% feed transfer and energy use improvements, with complete reliance on non-utilized side-streams; HP_LT – HP scenario involving 25% feed transfer and energy use improvements, with complete reliance on non-utilized side-streams and alternative energy sources; HM – *H. illucens* meal (defatted protein concentrate); HM_ST – HM scenario involving 25% feed transfer and energy use improvements; HM_MT – HM scenario involving 25% feed transfer and energy use improvements, with complete reliance on non-utilized side-streams; HM_LT – HM scenario involving 25% feed transfer and energy use improvements, with complete reliance on non-utilized side-streams and alternative energy sources;* – category calculated with IMPACT World + Midpoint V0.04.

Table 2A
Environmental impact comparison of main protein sources used for feed and food (per 1 kg of product)

	DM %	Protein, %	GWP, kg CO_2 eq.	OD, mg CFC11 eq.	AC, g SO_2 eq.	EU, g N eq.	ED, MJ	FD, m^3	LU, m^2a
Soybean meal	87.5[1]	49.1[1]	0.34-0.72[1] 6.52[19]	0.2-0.3[1,17]	−1.2 – 3.1[1] 11.4[17]	−81-2[1] (g NO_3 eq.)	5.37[6] 25.5[19]	0.04[6]	3.26[6]
Rapeseed cake	89[1]	34.8[1]	0.37-0.57[6]	0.004-0.05[6]	6.8-7.5[6]	8.9-9.1[6]	3.3-3.8[6]	0.001-0.03[6]	1.5-1.6[6]
Pea protein meal	n/a	n/a	0.44[6] 4-10[8] (pulses)	0.057[6]	21.8[6]	7.94[6]	5.25[6]	0.03[6]	2.85[6]
Fishmeal	90[4]	60-72[5]	0.12-0.58[18] 0.65-1.8[14,3,4,13] 0.48-5.6[15,16] 5.37[17]	0.016-0.073[18] 0.83[3] 0.947-1.03[17,4]	0.12-8.7 [14,18] 7.0[13] 15.9-18.0[4.16] 56.7-62.6[19,3]	−16[4] 0.4-0.87 [3.18]	2.13-17.1[18,4,3] 21[13] 79.8[17] 120[16]	0.0002-0.0016[18] 0.0036[3] 0.347[4]	0.0005-0.0052[18,3] 0.6-1.1[14]
HM (this study)	96.6	56	5.3	0.43	21.3	17.9	84.18	0.0028	1.89
HP (this study)	30	17	1.16	0.091	5.3	4.6	17.9	0.0006	0.48
Fresh meat (chicken)	25-30	23-24	1.62-3.12[10]	1.8[10]	44.25[10]	75[10] (g NO_3 eq.)	18.5-65[10]	0.053-0.155[11]	19.5-31.3[11]
Whey concentrate	86-89[3]	60[3,7] 80[11,kp]	7.48[7] 0.8-7.4[6] 12.1[2] 28–43[8,kp] 40.6[11,kp]	0.01-0.06[9] 3.33[7] 3.8[11,kp]	0.05-1.5[6] 56.6[7]	1.14[6] 37.3[2] 3.59-101[9] 229.3[11,kp]	58.1[2] 83.3[7] 10.7-39.4[6]	0.003-0.066[6] 1.45[2] 9.58[7]	0.26-8.27[6]
Egg protein concentrate[9]	85	80	23.4	1.01	4000	139	183	2.65	40.1
Microalgae[9]	96	55	14.7-245.1	0.9-19.8	260.5-1407.5	40.6-105.3	217.1-4181.3	0.3-3.9	1.7-5.4

Sources: [1] – (Dalgaard et al., 2008); [2] – (Kim et al., 2013); [3] – own calculations, [4] – Danish LCA Food Database; [5] – (Hall, 2011); [6] – ecoinvent 3 and Agrifootprint databases; [7] – (Smetana et al., 2016); [8] - (Nijdam et al., 2012); [9] – (Smetana et al., 2017); [10] – (González-García et al., 2014; Weidema et al., 2008); [11] – (Wiedemann et al., 2017); [12] – (Bacenetti et al., 2018); [13] – (Papatryphon et al., 2004); [14] – (Samuel-Fitwi et al., 2013); [15] – (Cashion et al., 2017); [16] – (Smárason et al., 2017); [17] – (Silva et al., 2017); [18] – (Fréon et al., 2017); [kp] – per kg protein. Note: HP – *H. illucens* puree (fresh insect production); HM – *H. illucens* meal (defatted protein concentrate); DM – dry mass, GWP – global warming potential; OD – ozone depletion; AC – acidification; EU – eutrophication; ED – energy demand; FD – freshwater depletion; LU – land use.

Table 3A
Impact results for midpoint categories (C-LCA, IMPACT 2002+, FU: increase in market demand for 1 kg of product with the substitution of alternative benchmark product)

Impact category	Unit	IF_F	HM_F	HP_M	HP_MC	HP_MA	HM_S	HM_SC	HM_SA	HM_F	HM_FC	HM_FA
Carcinogens	kg C_2H_3Cl eq.	0.399	0.965	0.191	0.002	−0.016	0.989	0.080	−0.006	0.965	0.056	−0.030
Non-carcinogens	kg C_2H_3Cl eq.	0.214	−0.029	−0.003	0.013	−0.056	0.057	0.132	−0.196	−0.029	0.046	−0.282
Respiratory inorganics	g $PM_{2.5}$ eq.	−0.010	0.008	−2.908	−5.076	−5.965	7.977	−2.470	−6.755	7.758	−2.689	−6.974
Ionizing radiation	Bq C-14 eq.	−27.883	78.245	−2.914	−9.255	−12.938	79.299	48.745	30.998	78.245	47.690	29.944
Ozone layer depletion	mg CFC-11 eq.	−0.379	0.274	0.094	−0.055	−0.097	1.065	0.349	0.143	0.274	−0.442	−0.648
Respiratory organics	g C_2H_4 eq.	−1.119	3.769	0.422	−0.503	−0.693	4.422	−0.034	−0.952	3.769	−0.687	−1.605
Aquatic ecotoxicity	ton TEG water	4.627	6.766	1.329	0.050	−0.048	7.070	0.908	0.435	6.766	0.605	0.132
Terrestrial ecotoxicity	ton TEG soil	1.185	0.509	0.169	0.099	0.070	0.755	0.417	0.275	0.509	0.171	0.029
Terrestrial acid./nitri.	kg SO_2 eq.	−0.265	0.146	−0.238	−0.325	−0.318	0.186	−0.237	−0.202	0.146	−0.277	−0.242
Land occupation	m^2org.arable	−0.073	22.479	2.379	−2.334	−2.499	19.945	−2.762	−3.558	22.479	−0.229	−1.025
Aquatic acidification	g SO_2 eq.	−0.064	0.008	−36.054	−47.480	−47.184	14.005	−41.050	−39.620	8.151	−46.904	−45.474
Aquatic eutrophication	g PO_4 P-lim	0.001	0.014	1.607	−1.002	−1.406	12.692	0.123	−1.822	13.588	1.018	−0.926
Global warming	kg CO_2 eq.	−12.643	8.370	0.072	−1.276	−2.177	7.911	1.418	−2.924	8.370	1.876	−2.466
Non-renewable energy	MJ primary	−45.899	129.162	10.309	−4.211	−12.451	141.394	71.431	31.732	129.162	59.198	19.500
Mineral extraction	MJ surplus	−0.549	0.700	0.076	−0.040	−0.079	0.685	0.126	−0.063	0.700	0.140	−0.048
Water use*	L deprived	−0.008	0.104	−154.211	−175.591	−176.453	93.223	−9.794	−13.947	103.869	0.852	−3.301

Note: IF_F – organic insect fertilizer (dried and pelletized) with organic fertilizer production substitution; HP_M – *H. illucens* puree (fresh insect production) with chicken production (live weight) substituted; HP_MC – HP_M scenario with avoided need to compost non-utilized side-streams used as feed for insects; HP_MA – HP_M scenario with avoided need to treat non-utilized side-streams used as feed for insects (anaerobic digestion); HM_S – *H. illucens* meal (defatted protein concentrate) with soybean meal production substituted; HM_S – *H. illucens* meal (defatted protein concentrate) with soybean meal production substituted; HP_SC – HP_S scenario with avoided need to compost non-utilized side-streams used as feed for insects; HP_SA – HP_S scenario with avoided need to treat non-utilized side-streams used as feed for insects (anaerobic digestion); HM_F – *H. illucens* meal (defatted protein concentrate) with fishmeal production substituted; HP_FC HP_F scenario with avoided need to compost non-utilized side-streams used as feed for insects; HP_FA – HP_F scenario with avoided need to treat non-utilized side-streams used as feed for insects (anaerobic digestion); * – category calculated with IMPACT World + Midpoint V0.04.

Table 4A
List of background datasets used for Life Cycle modelling

Product name	Geography	ISIC class	Unit	Activity uuid
Ecoinvent 3.1				
transport, freight, lorry 3.5-7.5 metric ton, EURO4	GLO	Freight transport by road	metric ton*km	23c166a1-05ea-4e53-ab11-ab2e5fe59c90
tap water	Europe without Switzerland	Water collection, treatment and supply	kg	440a13d4-2419-4f0f-b763-788b0cb1656d
electricity, low voltage	NL	Electric power generation, transmission and distribution	kWh	5502a6e1-70a2-4897-b7cf-ac999c17bb10
wastewater, average	Europe without Switzerland	Sewerage	m3	6a2fa2b9-9af2-4cf6-a597-67049dc5731e
nitric acid, without water, in 50% solution state	GLO	Manufacture of fertilizers and nitrogen compounds	kg	bd6d3c3d-c7aa-4cb7-9d2a-1121105ddfd0
sodium hydroxide, without water, in 50% solution state	GLO	Manufacture of basic chemicals	kg	9767691f-fa5f-43cf-aa23-9f16ddad31ac
heat, central or small-scale, natural gas	Europe without Switzerland	Steam and air conditioning supply	MJ	e6746287-2217-4b58-96d0-96643fa1a0af
wastewater, average	Europe without Switzerland	Sewerage	m3	6a2fa2b9-9af2-4cf6-a597-67049dc5731e
soap	GLO	Manufacture of soap and detergents, cleaning and polishing preparations, pe	kg	3dd42551-745c-4f40-a97b-7adf58e4cd3f
zeolite, slurry, without water, in 50% solution state	GLO	Manufacture of soap and detergents, cleaning and polishing preparations, pe	kg	5d1d5d56-2746-4cdb-82c9-8bc15038607a
Distiller's Dried Grains with Solubles	GLO	Manufacture of prepared animal feeds	kg	1e0d8fa7-86f6-4a09-91bd-c5c00f6ecdb4
Agri-footprint				
Wheat middlings & feed, from dry milling, at plant, Economic	NL		kg	
Wheat starch slurry, from wet milling, at plant, Economic	NL		kg	

Table 5A
Life cycle inventory for the main resources required for the production and processing of *Hermetia illucens* used in the study

Production stages	Type of resources used	Amount/Unit
Feed transportation	Diesel	Truck 3.5-7.5 ton: 2.418 tkm / 1 kg of fresh larvae (average)
Feed handling:	Electricity	0.0025 kW h / 1 kg of feed (storing)
- Mixing		0.0175 kW h / 1 kg of feed (mixing)
- Storing		0.005 kW h / 1 kg of feed (transporting)
- Transporting (within company)	Drinking water	0.005 l / 1 kg of feed
		0.67 l / 1 kg of feed (cleaning)
Insect nursery	Electricity	1524.6 kW h / 1 kg of eggs
- Egg production	Natural gas	37.27 m^3 / 1 kg eggs
	Drinking water	50 m^3 / 1 kg of eggs (cleaning)
Insect rearing and breeding	Electricity	0.02 kW h / 1 kg fresh larvae (feeding)
- Feeding		0.43 kW h / 1 kg fresh larvae (climate system)
- Climate system		0.012 kW h / 1 kg fresh larvae (transporting)
- Transporting		0.1 kW h / 1 kg fresh larvae (utilities)
- Utilities	Natural gas	0.06 m^3 / 1 kg fresh larvae
	Drinking water	16.14 l / 1 kg of fresh larvae (cleaning)
Processing	Electricity	0.007 kW h / 1 kg fresh larvae (insect separation)
- Insect separation		0.005 kW h / 1 kg fresh larvae (product separation)
- By-products separation		0.009 kW h / 1 kg fresh larvae (grinding)
- Grinding		0.024 kW h / 1 kg fresh larvae (pelletizing)
- Pelletizing		0.139 kW h / 1 kg fresh larvae (extraction)
- Extraction		0.08 kW h / 1 kg fresh larvae (utilities)
- Utilities	Drinking water	10.76 l / 1 kg of fresh larvae (cleaning)
- Drying	Natural gas	0.04 m^3 / 1 kg fresh larvae (drying)
Product management	Electricity	0.076 kW h / 1 kg of product (storage)
- Storage		0.005 kW h / 1 kg of product (transportation)
- Transportation (within company)		0.034 kW h / 1 kg of product (utilities)
- Utilities	Drinking water	2.62 l / 1 kg of product (cleaning)
	Natural gas	0.02 m^3 / 1 kg of product (average)
Administrative areas support	Electricity	0.13 kW h / 1 kg fresh larvae
	Drinking water	1.82 l / 1 kg fresh larvae
	Natural gas	0.00422 m^3 / 1 kg fresh larvae

References

Allegretti, G., Talamini, E., Schmidt, V., Bogorni, P.C., Ortega, E., 2018. Insect as feed: an emergy assessment of insect meal as a sustainable protein source for the Brazilian poultry industry. J. Clean. Prod. 171, 403–412.

Bacenetti, J., Bava, L., Schievano, A., Zucali, M., 2018. Whey protein concentrate (WPC) production: environmental impact assessment. J. Food Eng. 224, 139–147. https://doi.org/10.1016/j.jfoodeng.2017.12.018.

Barragan-Fonseca, K.B., Dicke, M., van Loon, J.J.A., 2017. Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed–a review. J. Insects Food Feed 1–16.

Bosch, G., van der Fels-Klerx, H.J., Rijk, T.C., Oonincx, D.G.A.B., 2017. Aflatoxin B1 tolerance and accumulation in Black soldier fly larvae (*Hermetia illucens*) and yellow mealworms (*Tenebrio molitor*). Toxins (Basel) 9, 185.

Boulay, A.-M., Bouchard, C., Bulle, C., Deschênes, L., Margni, M., 2011. Categorizing water for LCA inventory. Int. J. Life Cycle Assess. 16, 639–651.

Camenzuli, L., Van Dam, R., de Rijk, T., Andriessen, R., Van Schelt, J., Van der Fels-Klerx, H., 2018. Tolerance and *excretion of the mycotoxins aflatoxin B1, zearalenone, deoxynivalenol, and ochratoxin a by alphitobius diaperinus* and *Hermetia illucens* from contaminated substrates. Toxins (Basel) 10, 91. https://doi.org/10.3390/toxins10020091.

Cammack, J.A., Tomberlin, J.K., 2017. The impact of diet protein and carbohydrate on select life-history traits of the Black soldier fly *hermetia illucens* (L.) (Diptera: Stratiomyidae). Insects 8, 56.

Cashion, T., Tyedmers, P., Parker, R.W.R., 2017. Global reduction fisheries and their products in the context of sustainable limits. Fish Fish. 18, 1026–1037.

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., Pengue, W.A., 2008. LCA of soybean meal. Int. J. Life Cycle Assess. 10, 240–254. https://doi.org/10.1065/lca2007.06.342.

Diener, S., Studt Solano, N., Roa Gutiérrez, F., Zurbrügg, C., Tockner, K., 2011. Biological treatment of municipal organic waste using Black soldier fly larvae. Waste Biomass Valoriz. 2, 357–363. https://doi.org/10.1007/s12649-011-9079-1.

Dortmans, B.M., Diener, S., Verstappen, B., Zurbrügg, C., 2017. Black Soldier Fly Biowaste Processing-A Step-by-Step Guide. Eawag-Swiss Federal Institute of Aquatic Science and Technology., Dübendorf, Switzerland.

Ekvall, T., Weidema, B.P., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Cycle Assess. 9, 161–171.

Elhag, O., Zhou, D., Song, Q., Soomro, A.A., Cai, M., Zheng, L., Yu, Z., Zhang, J., 2017. Screening, expression, purification and functional characterization of novel antimicrobial peptide genes from *Hermetia illucens* (L.). PLoS One 12, e0169582.

Fréon, P., Durand, H., Avadí, A., Huaranca, S., Moreyra, R.O., 2017. Life cycle assessment of three Peruvian fishmeal plants: toward a cleaner production. J. Clean. Prod. 145, 50–63.

Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J., van Zelm, R., 2013. ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Characterisation A life cycle impact…. doi:http://www.lcia-recipe.net.

González-García, S., Gomez-Fernández, Z., Dias, A.C., Feijoo, G., Moreira, M.T., Arroja, L., 2014. Life cycle assessment of broiler chicken production: a Portuguese case study. J. Clean. Prod. 74, 125–134. https://doi.org/10.1016/j.jclepro.2014.03.067.

Hall, G.M., 2011. Fish Processing: Sustainability and New Opportunities. John Wiley & Sons.

Halloran, A., Hanboonsong, Y., Roos, N., Bruun, S., 2017. Life cycle assessment of cricket farming in north-eastern Thailand. J. Clean. Prod. 156, 83–94. https://doi.org/10.1016/j.jclepro.2017.04.017.

Hu, E., Bartsev, S.I., Liu, H., 2010. Conceptual design of a bioregenerative life support system containing crops and silkworms. Adv. Sp. Res. 45, 929–939. https://doi.org/10.1016/j.asr.2009.11.022.

ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework.

ISO 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Robenbaum, R.K., 2003. Impact 2002+: a New life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8, 324–330. https://doi.org/10.1007/BF02978505.

Kim, D., Thoma, G., Nutter, D., Milani, F., Ulrich, R., Norris, G., 2013. Life cycle assessment of cheese and whey production in the USA. Int. J. Life Cycle Assess. 18, 1019–1035. https://doi.org/10.1007/s11367-013-0553-9.

Kok, R., 1983. The production of insects for human food. Can. Inst. Food Sci. Technol. J. 16, 5–18. https://doi.org/10.1016/S0315-5463(83)72012-2.

Kroeckel, S., Harjes, A.-G.E., Roth, I., Katz, H., Wuertz, S., Susenbeth, A., Schulz, C., 2012. When a turbot catches a fly: evaluation of a pre-pupae meal of the Black soldier fly (*Hermetia illucens*) as fish meal substitute — growth performance and chitin degradation in juvenile turbot (*Psetta maxima*). Aquaculture 364–365, 345–352. https://doi.org/10.1016/j.aquaculture.2012.08.041.

Larrea-Gallegos, G., Vázquez-Rowe, I., Wiener, H., Kahhat, R., 2018. Applying the technology choice model in consequential life cycle assessment: a case study in the Peruvian agricultural Sector. J. Ind. Ecol. https://doi.org/10.1111/jiec.12812.

Liu, X., Chen, X., Wang, H., Yang, Q., ur Rehman, K., Li, W., Cai, M., Li, Q., Mazza, L., Zhang, J., 2017. Dynamic changes of nutrient composition throughout the entire life cycle of Black soldier fly. PLoS One 12, e0182601.

Loponte, R., Nizza, S., Bovera, F., De Riu, N., Fliegerova, K., Lombardi, P., Vassalotti, G., Mastellone, V., Nizza, A., Moniello, G., 2017. Growth performance, blood profiles and carcass traits of Barbary partridge (*Alectoris barbara*) fed two different insect larvae meals (*Tenebrio molitor* and *Hermetia illucens*). Res. Vet. Sci. 115, 183–188.

Magalhães, R., Sánchez-López, A., Leal, R.S., Martínez-Llorens, S., Oliva-Teles, A., Peres, H., 2017. Black soldier fly (*Hermetia illucens*) pre-pupae meal as a fish meal

replacement in diets for European seabass (*Dicentrarchus labrax*). Aquaculture 476, 79–85.
Makkar, H.P.S., Tran, G., Heuzé, V., Ankers, P., 2014. State-of-the-art on use of insects as animal feed. Anim. Feed Sci. Technol. 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008.
Maurer, V., Holinger, M., Amsler, Z., Früh, B., Wohlfahrt, J., Stamer, A., Leiber, F., 2016. Replacement of soybean cake by *Hermetia illucens* meal in diets for layers. J. Insects Food Feed 2, 83–90. https://doi.org/10.3920/JIFF2015.0071.
Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37, 760–770. https://doi.org/10.1016/j.foodpol.2012.08.002.
Nyakeri, E.M., Ogola, H.J., Ayieko, M.A., Amimo, F.A., 2017. An open system for farming Black soldier fly larvae as a source of proteins for smallscale poultry and fish production. J. Insects Food Feed 3, 51–56.
Oonincx, D.G.A.B., 2017. Environmental impact of insect production. In: van Huis, A., Tomberlin, J.K. (Eds.), Insects as Food and Feed: From Production to Consumption. Wageningen Academic Publishers.
Papatryphon, E., Petit, J., Kaushik, S.J., van der Werf, H.M.G., 2004. Environmental impact assessment of salmonid feeds using life cycle assessment (LCA). AMBIO A J. Hum. Environ. 33, 316–323.
Purschke, B., Scheibelberger, R., Axmann, S., Adler, A., Jäger, H., 2017. Impact of substrate contamination with mycotoxins, heavy metals and pesticides on growth performance and composition of Black soldier fly larvae (*Hermetia illucens*) for use in the feed and food value chain. Food Addit. Contam. A.
Renna, M., Schiavone, A., Gai, F., Dabbou, S., Lussiana, C., Malfatto, V., Prearo, M., Capucchio, M.T., Biasato, I., Biasibetti, E., 2017. Evaluation of the suitability of a partially defatted Black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (*Oncorhynchus mykiss* Walbaum) diets. J. Anim. Sci. Biotechnol. 8, 57.
Rumpold, B., Schlüter, O., 2014. Nutrient composition of insects and their potential application in food and feed in Europe. Food Chain 4, 129–139.
Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., Savastano, D., 2017. Environmental impact of food waste bioconversion by insects: application of life cycle assessment to process using *Hermetia illucens*. J. Clean. Prod. 140, 890–905. https://doi.org/10.1016/j.jclepro.2016.06.154.
Samuel-Fitwi, B., Meyer, S., Reckmann, K., Schroeder, J.P., Schulz, C., 2013. Aspiring for environmentally conscious aquafeed: comparative LCA of aquafeed manufacturing using different protein sources. J. Clean. Prod. 52, 225–233.
Sánchez-Muros, M.-J., Barroso, F.G., Manzano-Agugliaro, F., 2014. Insect meal as renewable source of food for animal feeding: a review. J. Clean. Prod. 65, 16–27. https://doi.org/10.1016/j.jclepro.2013.11.068.
Silva, C.B., Valente, L.M.P., Matos, E., Brandão, M., Neto, B., 2017. Life cycle assessment of aquafeed ingredients. Int. J. Life Cycle Assess. 1–23.
Smárason, B.Ö, Ögmundarson, Ó., Árnason, J., Björnsdóttir, R., Davíðsdóttir, B., 2017. Life cycle assessment of Icelandic arctic char fed three different feed types. Turkish J. Fish. Aquat. Sci. 17, 79–90.
Smetana, S., Mathys, A., Knoch, A., Heinz, V., 2015. Meat alternatives: life cycle assessment of most known meat substitutes. Int. J. Life Cycle Assess. 20, 1254–1267. https://doi.org/10.1007/s11367-015-0931-6.
Smetana, S., Palanisamy, M., Mathys, A., Heinz, V., 2016. Sustainability of insect use for feed and food: life cycle assessment perspective. J. Clean. Prod. 137, 741–751. https://doi.org/10.1016/j.jclepro.2016.07.148.
Smetana, S., Sandmann, M., Rohn, S., Pleissner, D., Heinz, V., 2017. Autotrophic and heterotrophic microalgae and cyanobacteria cultivation for food and feed: life cycle assessment. Bioresour. Technol. 245, 162–170. https://doi.org/10.1016/j.biortech.2017.08.113.
Spranghers, T., Ottoboni, M., Klootwijk, C., Ovyn, A., Deboosere, S., De Meulenaer, B., Michiels, J., Eeckhout, M., De Clercq, P., De Smet, S., 2017. Nutritional composition of Black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. J. Sci. Food Agric. 97, 2594–2600.
Thévenot, A., Rivera, J.L., Wilfart, A., Maillard, F., Hassouna, M., Senga-Kiesse, T., Le Féon, S., Aubin, J., 2018. Mealworm meal for animal feed: environmental assessment and sensitivity analysis to guide future prospects. J. Clean. Prod. 170, 1260–1267. https://doi.org/10.1016/j.jclepro.2017.09.054.
ur Rehman, K., Cai, M., Xiao, X., Zheng, L., Wang, H., Soomro, A.A., Zhou, Y., Li, W., Yu, Z., Zhang, J., 2017. Cellulose decomposition and larval biomass production from the co-digestion of dairy manure and chicken manure by mini-livestock (*Hermetia illucens* L.). J. Environ. Manage. 196, 458–465.
van der Fels-Klerx, H.J., Camenzuli, L., van der Lee, M.K., Oonincx, D.G.A.B., 2016. Uptake of cadmium, lead and arsenic by tenebrio molitor and *Hermetia illucens* from contaminated substrates. PLoS One 11, e0166186. https://doi.org/10.1371/journal.pone.0166186.
van Huis, A., 2017. Insects as food and feed: perspective from a pioneer. In: SWISS ENTO FOOD Congress – 31 August 2017. ZHAW, Zurich.
van Huis, A., van Itterbeeck, J., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P., 2013. Edible Insects: Future Prospects for Food and Feed Security. FAO Forest. ed. FAO, United Nations, Rome.
van Zanten, H.H.E., Bikker, P., Meerburg, B.G., de Boer, I.J.M., 2018. Attributional versus consequential life cycle assessment and feed optimization: alternative protein sources in pig diets. Int. J. Life Cycle Assess. 23, 1–11. https://doi.org/10.1007/s11367-017-1299-6.
Wang, Y.-S., Shelomi, M., 2017. Review of Black soldier fly (*Hermetia illucens*) as animal feed and human food. Foods 6, 91.
Weidema, B., 2000. Avoiding co-product allocation in life-cycle assessment. J. Ind. Ecol. 4, 11–33. https://doi.org/10.1162/108819800300106366.
Weidema, B., 2003. Market Information in Life Cycle Assessment.
Weidema, B.P., Frees, N., Nielsen, A.-M., 1999. Marginal production technologies for life cycle inventories. Int. J. Life Cycle Assess. 4, 48–56. https://doi.org/10.1007/BF02979395.
Weidema, B., Wesnæs, M., Hermansen, J., Kristensen, I., Halberg, N., 2008. Environmental improvement potentials of meat and dairy products. Sci. N. Y. https://doi.org/10.2791/38863.
Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C.O., Wernet, G., 2013. Overview and Methodology. Data Quality Guideline for the Ecoinvent Database Version 3. Ecoinvent Report 1(v3). St. Gallen.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.
Wiedemann, S.G., McGahan, E.J., Murphy, C.M., 2017. Resource use and environmental impacts from Australian chicken meat production. J. Clean. Prod. 140, 675–684. https://doi.org/10.1016/j.jclepro.2016.06.086.