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Full length article

Black soldier fly larvae as an alternative feed source and agro-waste disposal route – A life cycle perspective

M. Beyers [a,b], C. Coudron [c], R. Ravi [a,b], E. Meers [b], S. Bruun [a,*]

[a] Department of Plant and Environmental Sciences, Faculty of Science, University of Copenhagen, Denmark
[b] RE-SOURCE LAB, Laboratory for BioResource Recovery, Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, Ghent, 9000, Belgium
[c] Inagro, Ieperseweg 87, Roeselare, 8800, Belgium

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ABSTRACT

Life cycle assessment (LCA) was applied to evaluate black soldier fly production using different diets, including typical Belgian agro-residues (Brussels sprout stems, endive roots and solid fraction pig manure). The LCA compared insect-based feed with soybean meal and fishmeal, and composting through insects versus conventional treatments. Underlying LCA data were derived through feeding experiments. To determine the sensitivity of the results, we tested the effect of alternative energy sources and dietary components.

Non-residue insect feed and energy use contributed greatly to overall environmental impacts. Insect protein had greater impacts than protein from soybean meal or fishmeal due to the high energy consumption and, in some cases, agro-product demands. These should be areas of focus to make European insect production more sustainable. In the case of Brussels sprout stems and endive roots, conventional treatments outperformed composting by insects. Between industrial versus insect pig manure composting, the results varied greatly by energy source and impact category.

1. Introduction

Livestock feed production threatens the world's ecosystems, climate and ability to support humankind. In the Farm to Fork Strategy, the EU Commission stresses that *sustainable and innovative feed additives* are inevitable if the *environmental and climate impact of animal production* is to be lowered, and that imports of *critical feed materials such as soya from deforested land* must be reduced (European Commission, 2020). The European Commission took a step in this direction by lifting the ban on processed animal protein (PAP) as feed for non-ruminant animals in 2021. Today insect PAP is not only allowed as fish feed, but as pig and poultry feed as well.

Given their nutritional composition and ability to digest a variety of organic substrates, the larvae of black soldier fly (*Hermetia illucens*) have been identified as valuable PAP (e.g. Abd El-Hack et al., 2020; van Huis et al., 2020). In addition, the larvae can convert organic waste and animal manure into valuable fertilisers (Amrul et al., 2022; Liu et al., 2022; Lopes et al., 2022). Insect production on residues is one of the few options available for fostering nutrient recycling and producing feedstuff within the EU that requires less land than current practices.

Flanders in Belgium is challenged by having a surplus of agro-residues such as endive (*Cichorium intybus)* roots, Brussels sprout (*Brassica oleracea)* stems and solid fraction pig manure. There is at present no valorisation strategy in place for endive roots, and current practice consists of reincorporating the roots to agricultural fields. Similarly, Brussels sprout stems are left to decompose as there is little incentive to co-harvest or utilise them further. Without a definite valorisation strategy in place, there is a high possibility of aerobic degradation of these agro-residues, leading to the emission of ammonia (Ruijter et al., 2013) and possibly of nitrous oxide and carbon. Additionally, Flanders has one of the highest livestock densities in Europe, resulting in manure surpluses and livestock feed deficits. This forces Flemish farmers to export surplus manure (and its constituent nutrients) to neighbouring countries every year (D'Haene and Vannecke, 2020), while Flanders itself has to import protein and energy feed from overseas since it is not self-sufficient. This nutrient imbalance presents a

Abbreviations: BSF, Black soldier fly; DM, Dry matter; EU, European Union; FU, Functional unit; LCA, Life cycle assessment; PAP, Processed animal protein; SI, Supplementary information.

* Corresponding author.
E-mail address: sab@plen.ku.dk (S. Bruun).

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predicament for the region.

Black soldier fly (BSF) larvae could play an important role in making nutrient flows in Flemish agriculture more circular by offering a way to upcycle agro-residues and by serving as PAP. However, BSF originate from the topics and their rearing in Europe requires substantial heating. Furthermore, diets composed solely of agro-residues often do not meet the dietary requirements of BSF larvae and therefore additional feed is needed. The aim of this study was to assess these issues and other trade-offs numerically using life cycle assessment.

Previous life cycle assessment (LCA) studies have evaluated BSF production using brewery side-streams and vegetable waste to replace fish feed mixtures for Norwegian salmon (Modahl and Brekke, 2022), side-streams from alcohol and beer production to produce human and livestock feed and organic fertiliser (Smetana et al., 2019), and animal manure and organic waste to produce food and feed (Smetana et al., 2016). These studies assumed that the insect production was taking place in Germany. While they evaluated the environmental impacts of waste-derived insect diets, none assessed black soldier fly production with diets consisting partly or entirely of agro-residues that are usually incorporated into agricultural fields. To the authors' knowledge, no LCA study has assessed BSF production on diets containing endive roots, Brussels sprout stems or solid fraction pig manure. This study is therefore the first to look specifically at Belgian conditions as being representative of EU regions with intensive animal production, and includes the avoidance of the most common treatment of the abovementioned agro-residues.

The objective was to assess the environmental performance of black soldier fly production as an alternative protein source, with different BSF diets containing agro-residues and solid manure.

In the section below, the goal and scope of this study and insect rearing experiments are presented and an explanation given of how the inventory data were gathered. In the results section, the environmental performance of each diet is evaluated and BSF-derived protein feed compared with protein feed from conventional sources. Furthermore, the environmental performance of composting through BSF larvae compared with conventional disposal routes is demonstrated. Finally, the opportunities and drawbacks of introducing insect production as a nutrient recycling method are discussed.

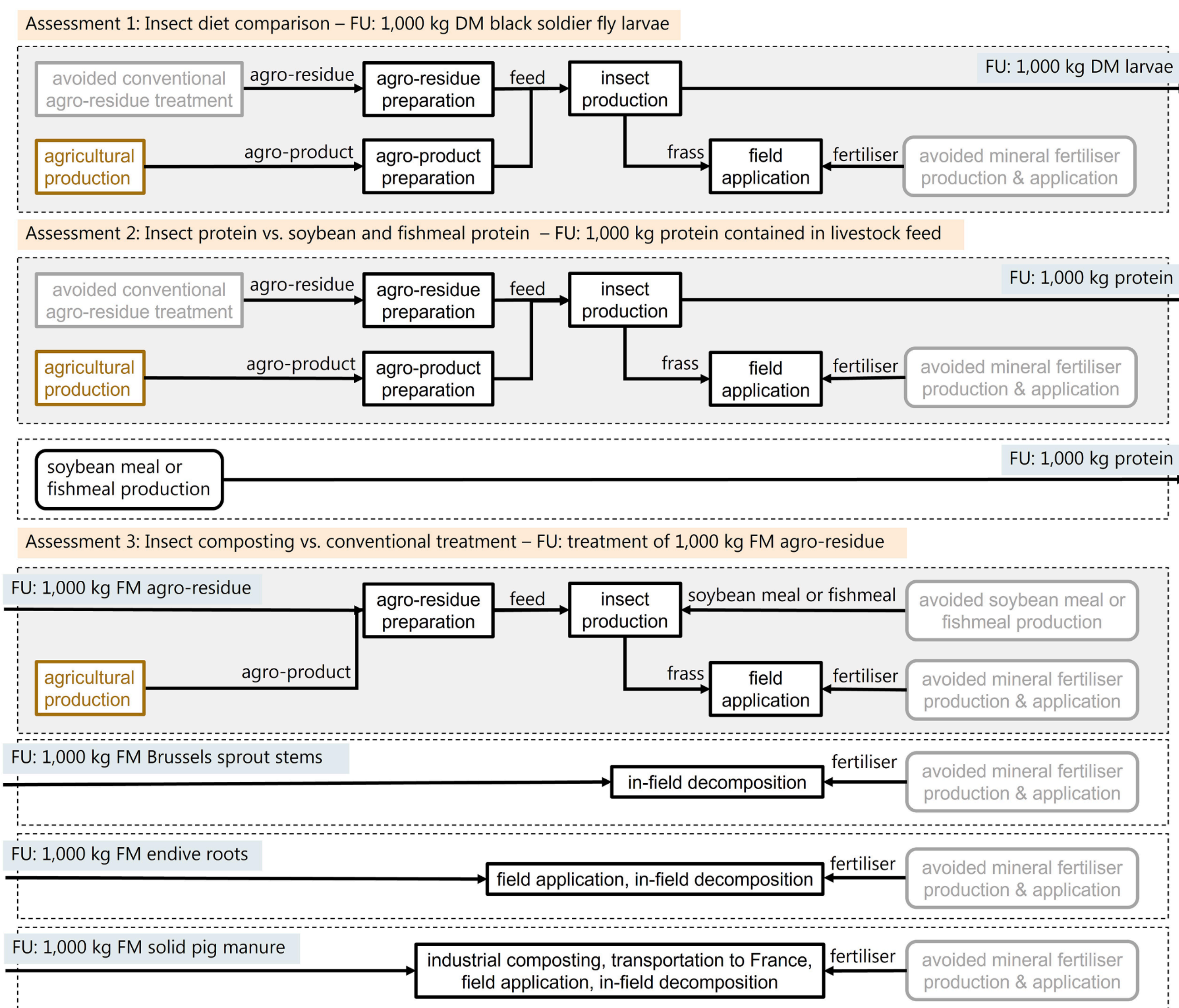


Fig. 1. Illustration of insect production systems analysed in the three assessments. Square boxes indicate activities in the foreground system, rounded boxes indicate activities in the background, arrows indicate exchanges. FU = functional unit (blue background), DM: dry matter, FM: fresh matter. Grey boxes: credits for avoidance, brown boxes: only valid for non-manure diets. Light grey background: insect system under study, white background: baseline scenarios Unless otherwise specified, 'agro-residue' represents any agro-residue studied here and differs between scenarios. Please note that [insect production] consists of two parts: 'egg to larvae' with the same feed across all diets, and 'insect rearing' with the different experimental diets (due to space and better readability the two stages are combined in the figure).

2. Methodology

Life cycle assessment was the main method used in this study. Consequential LCA modelling was applied to study the effect of insect production and the redirection of agricultural waste streams on related processes. The model was implemented in the open-source software openLCA v1.10.3 (https://openlca.org).

2.1. Goal & scope of the LCA study

The LCA took a multi-dimensional approach in order to understand the various environmental implications of insect production. Three different assessments and functional units (FU) were included:

Assessment 1: comparison of the environmental impacts of *different insect diets* to produce BSF larvae

FU 1: production of 1,000 kg dry matter BSF larvae

Assessment 2: comparison of the environmental impacts of *BSF and soybean meal or fishmeal as a feed protein source for livestock animals* such as pigs and poultry

FU 2: provision of 1,000 kg protein contained in livestock feed

Assessment 3: comparison of the environmental impacts of *BSF composting and conventional agro-residue treatment* of the same residues

FU 3: treatment of 1,000 kg fresh matter agro-residue

Fig. 1 provides a schematic description of the three assessments. All insect-related assessments (the top part of each assessment in Fig. 1) start with insect feed provision, continue with the rearing process, and end with insect harvesting and frass disposal. Frass refers to insect excrement, residual organic matter and dead insects. Organic matter is considered as composted by an insect after it has been eaten, digested and excreted at least once. Agro-residue is a generic term and residues varied between diets. The lower parts of assessments 2 and 3 in Fig. 1 describe the baseline systems. For assessment 2, this is the protein sources commonly used for livestock and for assessment 3 it is the common treatment pathways of studied agro-residues.

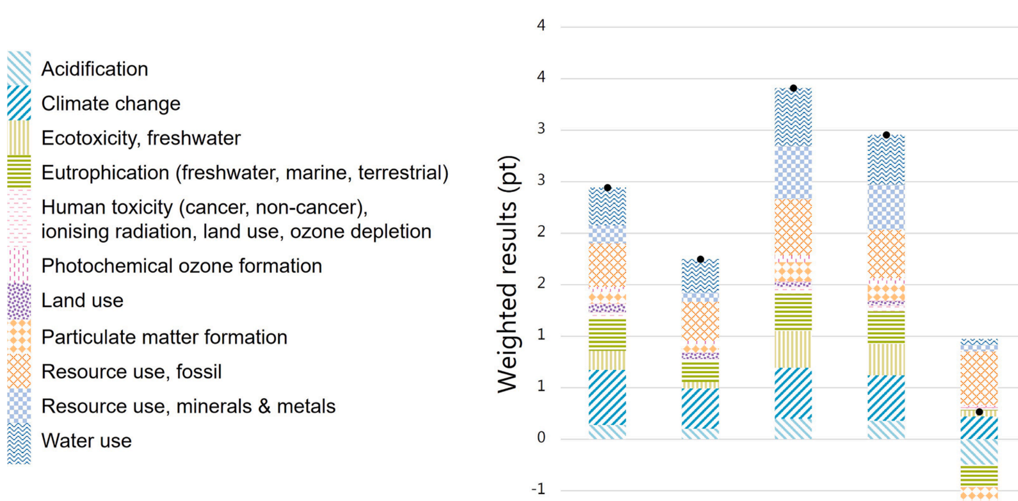
2.2. Data sources and inventory

Experimental data provided by Inagro, Belgium provided the foundation for the LCA inventory. Their data were supplemented by literature data, mass balancing and (modified) ecoinvent processes (v3.7.1 consequential) (Moreno Ruiz et al., 2020).

Inagro's experiments include the production of seven-day old larvae from eggs and subsequently ready-to-harvest larvae on experimental diets (Coudron, 2020). For the production of seven-day old larvae, BSF eggs were taken from Inagro's ongoing BSF production. After hatching, the young larvae began feeding on a starter feed consisting of chicken feed mixed with water. After seven days, the larvae were divided into separate crates and provided with an experimental diet. The experimental diets either consisted solely of agro-residues or of a mix of agro-residues and non-residues (for example chicken feed). To meet their dietary requirements, formulated diets (except for pure pig manure) had to consist of 30% dry matter (DM), at least 10% protein (on DM basis) and 40% non-fibre carbohydrates (on DM basis). These restrictions resulted in five diets, four based on crops and vegetables and one based on solid fraction pig manure. The crop and vegetable diets contained either Brussels sprout stems or endive roots or both. Fig. 2 gives an overview of all the diets and their components. Inagro recorded the growth performance, feed conversion ratios and nutritional composition of diets, and harvested larvae and the remaining organic matter (frass). More information can be found in the supplementary information (SI).

2.2.1. Data inventory: agro-residues

To model agro-residues, all necessary steps were included before feeding the agro-residues to the insects as well as the avoided conventional treatment. Currently, Brussels sprout stems are left in the field to decompose (conventional treatment scenario). Feeding them to insects requires their harvest and transportation (insect production scenario). Endive roots are reapplied to fields (conventional treatment) because unlike Brussels sprouts, endives are cultivated indoors. The solid fraction of pig manure is mainly composted and exported to P-deficient



	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
Brussels sprout stems*			80.1	65.3	
Chicken feed		23.5			
Endive root*	49.4	76.5		14.4	
Potato starch	16		19.9	19.9	
Soy paste	14				
Wheat bran	20.6			0.4	
Pig manure (solid fraction)*					100
Total [%]	**100**	**100**	**100**	**100**	**100**

Fig. 2. Upper bar diagram: weighted results for each insect diet per functional unit of 1,000 kg DM larvae (assessment 1). Lower table: composition of each diet in%. * indicates agro-residues, all other components are non-residues and thus agricultural products.

regions in France (conventional treatment). If fed to insects, endive roots and manure need to be transported to insect farms. Avoiding field application saves emissions from decomposition, but increases the requirement for nitrogen, phosphorous and potassium mineral fertilisers. Table 1 gives an overview of the stages included in conventional agro-residue treatments and insect production.

2.2.2. Data inventory: non-agro-residues

For non-agro-residues, ecoinvent processes were modified to resemble the characteristics in the feeding experiments. For instance, the dry matter content of potato starch in ecoinvent mismatched that of the starch used in the feeding experiments. Therefore, the ecoinvent process was scaled accordingly. For an overview of all adjustments made to the ecoinvent processes, please refer to Section 2.2 in the SI.

2.2.3. Data inventory: insect production

The insect production included the hatching of BSF eggs that are nourished by a mixture of chicken feed and tap water (referred to as 'egg to larvae rearing'), and the subsequent rearing of ready-to-harvest larvae (referred to as 'insect rearing'). Emissions from feed and frass decomposition as well as insect metabolism were included and the energy, electricity and water needed during the production taken into account. It should be noted that black soldier flies originate from the tropics and only develop well in temperatures of around 30 °C (Chia et al., 2018).

It was assumed that the insect frass was dried, transported and field applied as organic fertiliser in France. For the avoidance of the conventional agro-residue treatment, a reverse logic was applied to the logic used in the inventory and included emissions from frass field application as well as the replacement of mineral fertilisers.

2.2.4. Energy and materials consumption, remaining emissions

To account for energy and material consumption as well as emissions and mass flows between different compartments and insect production stages, information came from literature sources and mass balancing was undertaken (e.g. following the example of Parodi et al. (2020, 2021) and Smetana et al. (2019)). For detailed information, please refer to the SI.

In assessment 2, insect larvae replace soybean meal or fishmeal. For both, ecoinvent processes were used. Assessment 3 did not require additional data, merely a restructuring of collected data.

2.3. Life cycle impact assessment

For the impact assessment, the Environmental Footprint 3.0 methodology was selected (Fazio et al., 2018) because it has been developed for Europe and allows straightforward normalisation and weighting. Since no Product Environmental Footprint Category Rule has been developed for insect production, the general recommendations of the Product Environmental Footprint (PEF) Method (Annex I of PEF) were followed as much as possible (European Commission, 2021). Normalisation facilitates the comparability of impact categories and creates dimensionless point values. These uniform values reflect the environmental pressure caused by an average global citizen during one year and replace the different units of each impact category (EC-JRC, 2012). Weighting reflects the perceived relevance of each category. Weighting factors are applied to the normalised results. When combined, they allow a rating of impact categories (from greatest to least concerned) and scenarios (least and most favourable alternative). After identifying hotspots, a sensitivity analysis was performed to measure the response to changes in highly impactful processes.

These highly impactful processes included heating during insect production, and potato starch provision as a non-residue dietary component. To assess different heat sources, ecoinvent processes were used for renewable energy sources, including biogas (a-b global and Swiss), biogas from grass (c), a mix of natural gas and biomethane (d), wood pellets (e), and no heating, assuming residual heat from server rooms or a warmer climate (f). See section 3.7 in the SI for details.

An alternative to starch from potatoes grown for starch production is recovered starch, which is a by-product of the potato-processing industry. The inventory for the potato starch by-product was taken from an LCA study on starch-based jet fuel versus kerosene in the Netherlands (Moretti et al., 2022). Moretti et al. (2022) conducted consequential modelling and identified livestock feedstuff as a marginal product. Their approach was adopted in the present study and the additional need for livestock feed taken into consideration in the scenario analysis (Table A.46).

Table 1
Overview of processes included in conventional agro-residue treatments and their equivalent in the insect-based treatment.

Agro-residue to be treated	Conventional treatment	Treatment involving insect production
Brussels sprout stems	In-field decomposition[1]	Harvest, transportation, insect production
Endive roots	Field application & in-field decomposition[1]	Transportation, insect production
Solid fraction pig manure	Industrial composting, transportation to France, field application & in-field decomposition[1]	Transportation, insect production

[1] including emissions and avoidance of production and application of mineral NPK fertiliser.

3. Results

This section consists of four parts: (i) a comparison of insect diets, (ii) a comparison of insect protein versus soybean meal or fishmeal protein, (iii) a comparison of composting through BSF versus conventional agro-residue treatment, and (iv) scenario analyses. The most important impact categories and most relevant life cycle stages of the selected impact categories are shown in Fig. 3. More information can be found in the SI.

3.1. Assessment 1: Comparison of insect diets (FU: 1,000 kg DM BSF larvae)

Overall, the manure diet (diet 5) indicated the lowest environmental impacts, while diet 3, comprising Brussels sprout stems as the agro-residue and potato starch as the non-agro residue, indicated the greatest impacts. Of the non-manure-based diets, diet 2, consisting of endive roots and chicken feed, performed best (see Table A.23 for detailed results).

All the diets followed a similar pattern with respect to the impact categories of greatest and least concern (Fig. 2). Fossil resource use potential seemed to be of great importance in all diets. Across all the diets, the life cycle stage contributing most to fossil resource use was 'egg to larvae rearing' (SI Tables A.28 to A.32), with natural gas producing the highest impact contributions (SI, Table A.35).

Apart from the use of fossil resources, diets could be divided into two groups based on the impact categories where they had the greatest effect: group one contained the non-manure-based diets (diets 1 to 4) and group two the manure-based diet (diet 5).

In the non-manure-based diets, climate change potential had the highest relevance in diets 1 and 2, and ranked fourth in diet 3 and third in diet 4. The life cycle stages contributing most to climate change were 'diet provision' followed by 'insect rearing'. Climate change, like fossil resource use potential, was linked to natural gas used to heat the insect production facilities. Natural gas consumption was identified as highly impactful. Another highly impacted category was water use potential, which ranked highest in diets 3 and 4 and third in diets 1 and 2. Water use, like climate change, was dominated by 'diet provision', but it was in

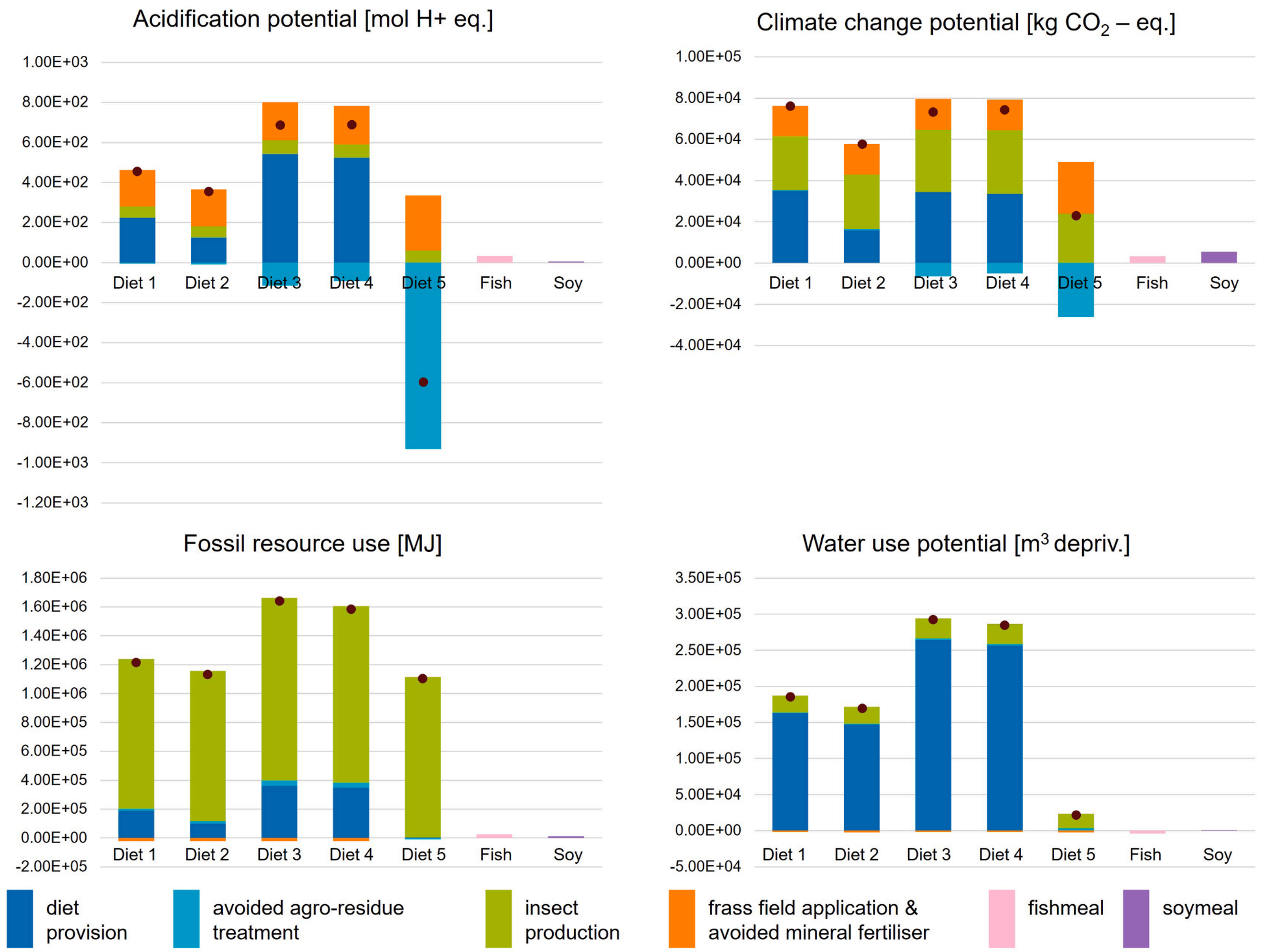


Fig. 3. Environmental impacts and contribution analysis of life cycle stages per FU of 1,000 kg protein contained in livestock feed for all insect diets and comparison with environmental impacts of 1,000 kg protein supplied through soybean meal or fishmeal.

water use that its contribution was most striking. In general, 'diet provision' was suggested to be an extremely important life cycle stage. Whenever potato starch was part of the non-manure dietary mix, its environmental impacts were found to have the greatest overall impact share, and dominated the categories of particulate matter formation, mineral resource use and acidification potential (cf. Table A.35).

While non-manure-based diets only suggested environmental burdens, manure-based diets could be beneficial to the environmental in some categories. In the manure-based diet (diet 5), the two most important impact categories following fossil resource use were acidification and particulate matter formation potential. Both impact categories proposed net negative impacts (cf. Fig. 1). The beneficial impacts of diet 5 arose from the avoidance of the conventional treatment of pig manure including transportation, industrial composting and field application, and to a lesser extent from the avoidance of mineral fertiliser through field application of insect frass (see Fig. 3 for acidification potential and Table A.32 in SI for an overview of the contributing life-cycle stages to all relevant impact categories).

3.2. *Assessment 2: Black soldier fly versus soybean meal or fishmeal protein (FU: 1,000 kg protein contained in livestock)*

When comparing conventional versus insect protein, soybean meal and fishmeal seemed to outperform insect protein from an environmental perspective. Soybean meal and fishmeal outperformed insect larvae derived from diets 1 to 4 in all impact categories and underperformed insect larvae derived from diet 5 in the categories of acidification, particulate matter formation and terrestrial eutrophication potential. These categories ranked second, third and fourth after normalisation and weighting. However, insects performed worse in terms of fossil resource use, ranking first.

3.3. *Assessment 3: BSF composting versus conventional agro-residue treatment (FU: treatment of 1,000 kg fresh matter agro-residue)*

The comparison of conventional agro-residue treatments with insect composting showed a similar impact pattern to that of conventional protein versus insect protein: treating plant-based agro-residues through insects resulted in greater environmental impacts, while the findings for the treatment of manure-based agro-residues were ambiguous.

When comparing disposal routes, the conventional endive root treatment had larger impacts than that of Brussels sprout stems. This can be attributed to the fact that the roots are transported and reapplied to the field, while the stems need no further handling. In terms of field emissions, the impacts were reversed. The decomposition of Brussels sprout stems resulted in greater N_2O, NH_3, and NO_3 emissions per hectare than that of endive roots. Providing Brussels sprout stems to insects produced greater impacts because the stems need to be harvested. Overall, using endive roots as insect feed seemed more promising than Brussels sprout stems. However, in neither case did insect composting appear favourable to conventional handling.

Avoiding the treatment of pig manure was more beneficial: storage, composting and field emissions were greater in the conventional system than in the insect system. This produced environmental improvements in acidification, marine and terrestrial eutrophication, and particulate matter formation potential. However, when considering all impact categories, the conventional treatment seemed favourable compared with composting by BSF larvae because of the additional needs for materials and energy that affect categories that are related less to direct manure or frass emissions (e.g. fossil resource use potential) (cf. Table A.41).

The results suggest the importance of the dry matter content of agro-residues because transportation is a major contributor to several impact categories (e.g. climate change and fossil resource use potential). Transporting the water contained in the residue generates emissions but provides insects with zero or little nutritional value. When selecting residues suitable for insect rearing, the dry matter content should be considered.

3.4. Scenario analyses

In the scenario analysis, the comparison of protein sources (Assessment 2) was revisited in light of the current and potential future development of EU policy. Given the perils of climate change and its effects on crop productivity, soy might no longer be a viable option or be available in sufficient quantities. Fish, another conventional protein source, is a limited resource and stocks are depleting. Both options are known to have environmental impacts such as biodiversity loss and species extinction, which are not sufficiently reflected in LCAs (Gaillet et al., 2022). Finding alternatives to soy and fish is therefore important and the question to ask might be *how* insect production can be made more sustainable.

The scenario analysis explored opportunities for decreasing the environmental impact of insect production. Given their great contributions, the response to alternatives to the Belgian natural gas mix as well as to industrial potato starch was tested (Fig. 4).

3.4.1. Energy supply to insect rearing facility

The weighting of the impact categories suggested fossil resource use potential to be of great concern during insect production. The major contributor to fossil fuel consumption was the natural gas needed to heat the insect farm. When comparing different heating sources to the default Belgian gas mix, all alternatives had both advantages and disadvantages. When applying normalisation and weighting, switching to biogas from grass (c) or residual heat (f) reduced the overall environmental impact of insect production based on manure below that of insect production based on soy (both) and fish (residual heat only) (Fig. 4). In all other diets, a switch would not be sufficient.

3.4.2. Potato starch supply as an insect diet component

Hotspot analyses of life cycle stages and processes suggested that diet provision in general and potato starch provision in particular caused great environmental burdens. Diets 1 and 4 comprised potato starch and were chosen as sample diets.

Switching to a by-product from the potato processing industry, suggested a decrease in environmental impacts. The greatest reductions were achieved in freshwater ecotoxicity, water use, terrestrial eutrophication, acidification and particulate matter formation potential, with reductions of around 25–35% in diet 1 and 65–80% in diet 4. Such a strong response to a change in a single component stressed the significance of potato starch provision. Despite great reductions, switching from industrial starch to by-product starch was insufficient for insect larvae to compete with soybean meal or fishmeal. In only one category (freshwater eutrophication potential) did diet 4 perform better than soybean meal. Fishmeal exhibited lower impacts in all categories. Switching from potato starch product to by-product can only be part of the solution.

When combining by-product potato starch with renewable heating sources or residual heat, insect protein came closer to being able to compete with soybean meal or fishmeal.

4. Discussion

This study compared the environmental implications of different insect diets, assessed the suitability of BSF larvae as an alternative protein source, and evaluated ways to upcycle three common agro-residues in Flanders. The effects of dietary choices on environmental impacts and the suitability of insects as a protein source and agro-residue management option are discussed below.

4.1. Assessment 1: Comparison of insect diets (FU: 1,000 kg DM BSF larvae)

A review conducted by Smetana et al. (2021) of 24 LCAs found consensus regarding the environmental hotspots of insect production. These hotspots are insect feed provision and energy use for insect production and processing, and are associated with impacts on fossil resource, water, land use and climate change (Smetana et al., 2021). Similar hotspots were found in the present study, even when replacing parts of the commercial feed with agro-residues. Amongst the non-manure-based diets (diets 1–4), non-residue diet provision and energy supply for insect production appeared to have the greatest environmental impact. As in the review by Smetana et al. (2021), this translated into adverse effects on the climate and on fossil and aquatic

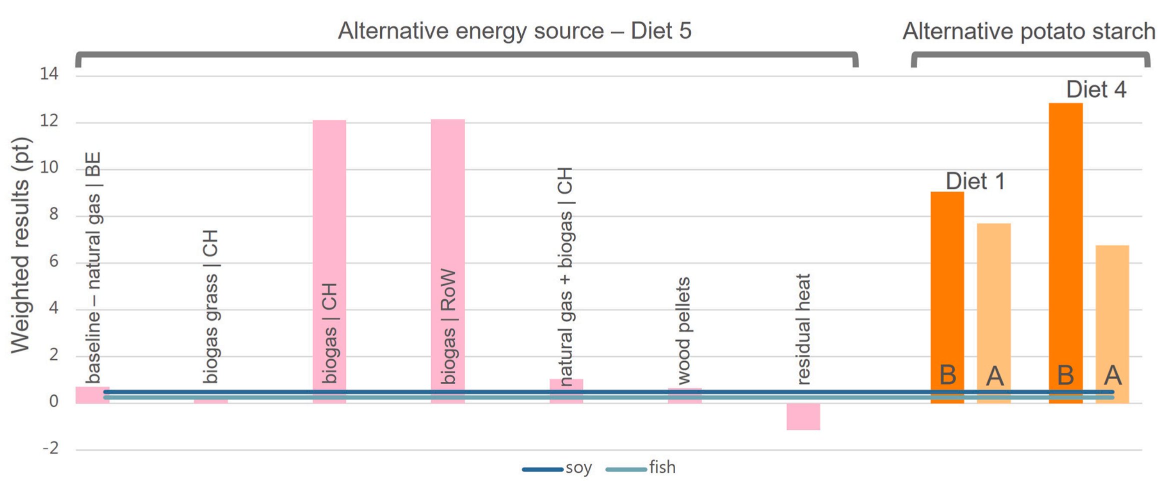


Fig. 4. Normalised and weighted results of the sensitivity analyses, per 1,000 kg protein. Alternative energy supply only for the manure-based diet. Alternative potato starch supply for diets 1 and 4. B: **B**aseline with potato starch as product; A: **A**lternative with potato starch as by-product.

resources. The only difference between the findings of this study and the review of Smetana et al. (2021) were in relation to the impact on land use potential because the present study found acidification, mineral resource use and freshwater ecotoxicity, for example, to be more greatly affected than land use (cf. Fig. 2). However, in the reviewed studies, these categories were less represented and excluded from some assessments. By including a wider range of impact categories, the present study provides a more conclusive picture than earlier studies and highlights the risk of disregarding important impacts when determining assessment categories up front.

Switching to 100% agro-residues, as in the manure-based diet, changes the kind of environmental hotspots as well as where in the insect production process they occur. While energy consumption remains a concern, impacts from land application and decomposition of manure or frass become more important because residues are provided at low or even negative environmental costs. A previous study on manure-based insect diets that assessed the impacts of using chicken and cow manure as feed for insects found contradictory results. While a chicken manure-based diet was found to have environmental impacts comparable to those of other organic waste streams, cow manure was found to have lower and even beneficial impacts (Smetana et al., 2016). In the case of cow manure, positive impacts from waste reduction outweigh the negative impacts from insect production and frass handling, while for chicken manure the treatment of leftovers is a major hotspot in the system, thereby making it unfavourable. The environmental impacts of solid fraction pig manure appear to fall between those of cow and chicken manure. However, it should be noted that the study and the work of Smetana et al. (2016) are not directly comparable since (i) the frass is handled differently and (ii) the assignment of burdens or credits related to the provision of manure are modelled differently.

All three agro-residues are unfit for animal consumption and should, according to Smetana et al. (2019), be classified as non-utilised side-streams. Smetana et al. (2019) conclude that identifying suitable non-utilised side-streams determines whether insect production is developed and upscaled. The present study also found that agro-residues (endive roots and Brussels sprout stems) contributed little to the overall environmental impact of insect production. Impacts arose mainly from the requirement to mix them with actual agricultural products to meet the insects' dietary requirements. Diets consisting solely of agro-residues reduce efficiencies and postpone larval maturation. While diet-related savings on environmental impacts can be achieved, greater impacts from energy production arise as the duration of production cycles is extended (Smetana et al., 2016). Optimisation models could be used to develop an optimal constellation of energy sources and dietary components.

4.2. *Assessment 2: Black soldier fly versus soybean meal or fishmeal protein (FU: 1,000 kg protein contained in livestock)*

Past studies comparing BSF protein with conventional livestock feed had contrasting conclusions. Smetana et al. (2019) conclude that soybean meal and fishmeal production are environmentally superior if the insects are fed on commercially available side-streams. However, if the insects are fed on non-utilised side-streams, they could compete with soybean meal and potentially even fishmeal (Smetana et al., 2019). Another study by Smetana et al. (2016) concludes that insects fed on chicken manure or beet pulp perform worse than if they are fed on chicken feed and fishmeal, but that feeding the insects with cattle manure, organic municipal waste or distiller's grain could result in more sustainable protein feed. A third study by Modahl and Brekke (2022) concludes that BSF fed on distiller's grain (and vegetable waste in one scenario) provides less environmentally harmful salmon feed than the conventional mix of soy, wheat, fishmeal and fava beans.

In the present study, a switch to insect production could only be beneficial in some categories solely in the case of solid fraction pig manure as insect feed. Since the impacts of diet provision are critical, it is crucial to model dietary components and set up their inventory. In Smetana et al. (2019), it is unclear what the non-utilised side-streams comprised and how the avoidance of composting was modelled. In Modahl and Brekke (2022), side-streams were modelled based on economic allocation, which they themselves state as critical. Following that logic, the sustainability of insect production would depend on the cost ratio between product and by-product.

To date, there appears to be no consensus on the 'optimal' life cycle assessment modelling perspective. In the studies of Smetana et al. (2016, 2019), as in the present study, consequential modelling was applied, while Modahl and Brekke (2022) applied attributional modelling. Evidently, this is a small sample size, yet it suggests that the choice of modelling influences the results of the LCA.

4.2.1. *Scenario analyses*

Given the urgent need to find alternative protein sources, the possibilities for addressing identified hotspots of energy and potato starch use were explored.

One workaround was to opt for a renewable source of heating instead of natural gas. Another LCA study on black soldier fly larvae production found that energy supplied by photovoltaic systems decreased its impacts (Smetana et al., 2019). The present study found that in the non-manure-based diets, a switch to other heat sources would not be sufficient. Identifying and, most importantly, establishing sustainable energy sources is a cross-sectoral and cross-border challenge and is not specific to insect production. With new energy and electricity mixes evolving, it would be useful to reassess the environmental implications of insect production at regular intervals, while bearing in mind that the environmental performance of soy and fish in terms of energy use would also improve if alternative energy sources were implemented globally.

Another option could be to promote BSF production in warmer regions where heating is not required. Allegretti et al. (2018) found that BSF could be a viable protein source for the Brazilian chicken industry, which currently depends on soybean meal. Halloran et al. (2017) came up with similar findings on cricket production for human consumption in northern Thailand as an alternative to chicken production. Diet provision carried the greatest environmental burden, while energy consumption during production was zero. Both Brazil and Thailand have a favourable climate for BSF production and heating is unlikely to be required. It could be argued that a favourable strategy would be to produce BSF protein in tropical countries and then export it to regions with a temperate climate and/or regions that are net importers of protein feed. However, in the cases of Brazil and Thailand, it might be more reasonable to meet national demands first. The protein content of soy is greater than that of BSF, meaning that relatively less soy has to be transported compared with BSF. Brazilian soy would continue to be exported to colder regions and Thai imports could be redirected. Future LCA studies could look at optimal constellations.

The use of by-product potato starch reduced the environmental impact of insect production, but the decrease was insufficient to make it compatible with soybean meal or fishmeal. Previous studies have shown that beet pulp and distiller's grains are possible low-impact dietary components (Modahl and Brekke, 2022; Smetana et al., 2016). It could be useful to integrate a wider variety of Belgian agro-residues into the diets and assess whether nutritional requirements can be met by utilising these instead.

4.3. *Assessment 3: BSF composting versus conventional agro-residue treatment (FU: treatment of 1,000 kg fresh matter agro-residue)*

The present study is the first to compare the conventional handling of Brussels sprout stems, endive roots and solid fraction pig manure with their composting by insects. Previous studies including waste streams have focused on substrates that could also serve as feed for livestock directly, and found that under such circumstances, insect production cannot be said to be sustainable (Smetana et al., 2019). It was thought that the use of agro-residues unfit for livestock consumption would increase the sustainability of insect production. However, the present analysis suggests that insect production does not compete with current practices for handling Brussels sprout stems and endive roots. Other valorisation options for endive roots could be cascading biorefinery utilisation (Stökle et al., 2021) or utilisation as a co-substrate in biogas plants (Dobbelaere et al., 2015) or as a base material for alternative plastic production (Boldt, 2022). Another pathway for valorising Brussels sprout stems could be to feed them to cows as energy food or use them as feedstock in anaerobic digestion plants (Dobbelaere et al., 2015). These studies show that composting through insects is not the only alternative available, and future LCA studies should focus on endive root or Brussels sprout stem recycling individually and compare different utilisation pathways. As emissions from decomposition after field application played a major role in the environmental impact profile, alternative scenarios with residue incorporation by ploughing are also relevant.

In the case of conventional treatment versus insect manure composting, it is difficult to draw conclusions. If the major concern regarding pig manure composting is greenhouse gas emissions (Zhong et al., 2013), BSF composting could be a valuable option.

Under current EU legislation (No 1069/2009), insects fed on manure may not be used as a livestock feed ingredient. However, since manure is a natural food source for BSF and their larvae are a natural food source for chickens, it may be argued that legislation could be changed under certain conditions. Past experiments have shown that BSF develop well on manure harvested from or directly beneath slatted flooring holding pigs (Newton et al., 2005). This is possible because the prepupae leave their moist environment after fattening and migrate to a dry place to pupate. No mechanical separation of manure and larvae is needed, and insects could enter the system almost as burden-free as fish. Even if the larvae do not encounter ideal growth and fattening conditions and production might not be possible year round, this practice is low-tech and might create additional value for pig farmers because of faster manure degradation and the production of sellable larvae as chicken feed. Future studies could investigate the feasibility of such practices under European conditions, along with their environmental and economic implications.

5. Conclusions

The aim of current study was to assess the environmental implications of insect production for livestock feed production and agro-residue management.

Irrespective of the diet, the results indicated that insect production performs worse than conventional soybean meal and fishmeal as a feed source unless major changes are made to the location and/or heating source for insect production. Thus, it is premature to disregard insect production as a sustainable pathway for providing protein for animal feed, because there may be solutions to the specific problems encountered. The results also indicated that the balance between insect production and alternative protein sources depends greatly on the insect feed used and the source of energy for heating during insect production. Thus, investigations that identify circumstances under which insect production is favourable, such as the location, energy source, type of agro-residues and conditions of production, are required in order to make insect production sustainable and competitive with soybean meal and fishmeal.

Since additional inputs of supplementary feedstuff are needed to meet dietary requirements, this study suggests that insect production based on endive roots and Brussels sprout stems performs worse than the conventional pathway for handling these residues. Furthermore, the avoided impacts from conventional handling are insufficient to counteract the impacts of feedstuff production and energy demand. In the case of pig manure, BSF production might be a valuable alternative to the conventional treatment because the avoidance of composting and field application produces noticeable net environmental savings. However, a clear superiority of insect production could not be demonstrated. Case-by-case analyses potentially using individual weighting factors could be useful for supporting decisions and optimising production in specific cases. In addition, future studies could build on this study by expanding the geographical scope from a nutrient-surplus region such as Flanders to other locations. Similarly, as highlighted in this study with endive roots, it is important to build a robust life cycle inventory of the management of endemic agro-residues and their applicability as a BSF feed. Finally, it could be of interest to assess the environmental impacts of using BSF to produce fat and chitin.

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CRediT authorship contribution statement

M. Beyers: Conceptualization, Methodology, Visualization, Writing – original draft. **C. Coudron:** Data curation, Writing – review & editing. **R. Ravi:** Conceptualization, Methodology, Writing – review & editing. **E. Meers:** Conceptualization, Funding acquisition, Writing – review & editing. **S. Bruun:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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