

Article

Industrial Symbiosis in Insect Production—A Sustainable Eco-Efficient and Circular Business Model

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Abstract: Insect meal (IM) is a source of high-quality protein for aquafeed while insect oil (IO) is a source of fatty acids used in monogastric feed with identical or better performance than premium fishmeal (FM) or vegetable oils (VOs) respectively. Although insects' ability to feed on agricultural by-products and the entire valorization of insect products (IM, IO, frass) suggest insect production is sustainable, no studies have documented its environmental impact using industrial-scale production data. The present study is the first attributional life cycle assessment (A-LCA) based on data from an industrial-scale facility implementing an innovative symbiosis production model. This A-LCA was used to (i) assess the environmental performance of the symbiosis model vs. a no-symbiosis model and (ii) compare the environmental impacts of IM and IO production vs. their respective alternatives. The results revealed that the symbiosis model introduces a meaningful change in terms of environmental footprint by reducing CO₂ emissions by 80% and fossil resources depletion by 83% compared to the no-symbiosis model. The higher sustainability of the IM and IO produced using the symbiosis model was also demonstrated, as CO₂ emissions were reduced by at least 55% and 83% when compared to the best FM and VOs alternatives, respectively.

Keywords: industrial symbiosis; alternative protein; insect meal; insect oil; frass; sustainable production; environmental impact; circular economy; organic fertilizer

1. Introduction

Global food production has nearly tripled since 1960 to meet the demands of the growing population. Diet evolution has led to an increased need for animal protein: per capita fish food consumption grew from 9.0 kg in 1961 to 20.5 kg in 2018 [1] and per capita livestock consumption grew from 23.1 kg in 1961 to 43.2 kg in 2013 [2]. This increasing demand for animal protein also stimulated the demand for feed ingredients thereby intensifying the pressure on limited natural resources [3]. In this context, the Food and Agricultural Organization has pointed out the urgent need to use alternative feeds, as the requirement for traditional feed ingredients cannot be met even by the most optimistic forecasts [4]. In addition, the gap between the demand and supply of these ingredients is expected to widen in the upcoming decades. This provides a compelling reason to explore locally available feed ingredients.

Insects are part of the natural diet of multiple animals, and therefore several species have been investigated as potential sources of feed ingredients for fish, shrimp, poultry, and swine diets. Black soldier fly larvae (BSFL) have been identified as a source of high-quality protein and fatty acids necessary for animal development. Multiple studies performed with partial (50%) or total replacement

of fishmeal (FM) by BSFL meal in aquafeed clearly demonstrated the validity of the latter in terms of nutritional demands [5–7]. Similarly, studies evaluating the replacement of VOs by BSFL oil in monogastric feed demonstrated similar growth performance for broiler chicks [8] and young turkeys [9], as well as similar meat quality, nutritional composition, and sensory profile of finisher broilers [10] and young turkeys [9]. In addition to showing at least equal performance to FM and VOs in aqua and monogastric feed, two reasons suggest that IM and IO could also be more sustainable than their respective alternatives. First, insects have the ability to transform low-value agricultural by-products into high-quality feed because insect production has extremely low water and land requirements [5,7,11]. Second, insects can be valorized entirely: IM as a source of high-quality protein for aquafeed, IO as a source of energy and lauric acid for monogastric feed, and frass (insect dejections) as an organic fertilizer thus closing the loop on nutrient cycling [11–13].

However, to meet the world's current and future demands for animal feed ingredients, insect rearing must be performed at industrial scale [14] and references therein. Likewise, to provide the most accurate environmental impact analysis, it is also at this scale that the sustainability of producing IM and IO has to be determined [12] and compared to that of their traditional alternatives [15]. Thus, it is vital to perform a life cycle assessment (LCA) of the entire production process to provide insights on which step(s) encompass environmental challenges, and thoroughly assess how sustainable the production of IM and IO is compared to that of traditional feed ingredients such as FM and VOs [12]. Few studies have performed such LCAs on the environmental impact of insect production [13] and references therein and all were based on partial or aggregated data derived from pilot-scale facilities. Following the change in European legislation (EU Regulation 2015/2283), which enabled the use of insect-based protein in aquaculture feed in 2017, the construction of several large-scale insect production facilities was announced. InnovaFeed, a French biotechnology company, has developed a unique and innovative symbiosis model in which the insect production unit is co-located with agro-industrials to recycle the by-products of these industries as feed for the insects and to benefit from energetic synergies during insect rearing. InnovaFeed's industrial-scale insect production facility was inaugurated in 2020.

The present study aimed to analyze the environmental impact of this innovative symbiosis model for BSFL production at industrial scale. Firstly, an attributional LCA (A-LCA) was conducted to evaluate the environmental impact of the symbiosis production model. Secondly, this impact was compared to that of a model without symbiosis (hereafter referred to as “no-symbiosis model”) to evaluate the impact of the symbiosis. Finally, the environmental impacts of producing IM and IO using the symbiosis model were compared to that of producing their respective alternatives, i.e., FM and VOs, by contrasting the results from the current A-LCA with data available in the Agribalyse 1.3. database (<https://app.agribalyse.fr>) for these conventional feed ingredients.

2. Materials and Methods

2.1. Goal and Scope Definition of the A-LCA (ISO 14040)

To the best of our knowledge, the present A-LCA is the first using industrial-scale insect production data. Moreover, the environmental impact of producing IM, IO, and insect frass was based on data derived from InnovaFeed's industrial scale production facility in France that is co-located with two other industrial players: (i) a starch manufacturer that directly supplies local agricultural by-products to feed the larvae and (ii) a wood biomass turbine, installed in a renewable energy power plant, that powers the insect production facility. Using such data enabled assessing the potential environmental benefits of the symbiosis model vs. a no-symbiosis model but also the environmental impacts of the different production steps as well as that of each of the three products (IM, IO, and frass).

For the present A-LCA, the cradle-to-gate approach was used. It encompassed (i) feed preparation (raw materials' production and supply and BSFL feed preparation), (ii) BSFL growth and reproduction, (iii) IM and IO processing, and (iv) frass processing. These four steps are collectively referred to as “insect production” throughout the text.

To assess the environmental impact of the two different production models (symbiosis vs. no-symbiosis), 1 t IM + 0.35 t IO + 7 t frass was designated the Functional Unit (FU), as the three products were simultaneously produced at the 1:0.35:7 ratio at the insect production facility.

2.2. Inventory Analysis (ISO 14044)

2.2.1. Inventory Flows

The production of BSFL requires three types of inputs: (i) agricultural by-products (i.e., wheat bran and wheat slurry), (ii) food by-products both to feed BSFL; and (iii) energy to power the production facility. There are four output flows: three products (IM, IO and frass) and water.

In the case of the insect production facility examined here, agricultural by-products were supplied directly from the starch manufacturer located close to it via a pipeline connecting the two sites (Figure 1). As a result, agricultural by-products required no additional evaporation: wheat bran was provided with a dry matter (DM) content of 88% and wheat slurry with 15% DM; hence, no extra water was added to feed the BSFL. The co-location of the starch manufacturer and insect production facility also enabled the reception of slurry at 80 °C. The capture of this heat contributed to maintaining the appropriate temperature in the breeding zone thereby decreasing the overall energy needs of the insect production facility by 20%.

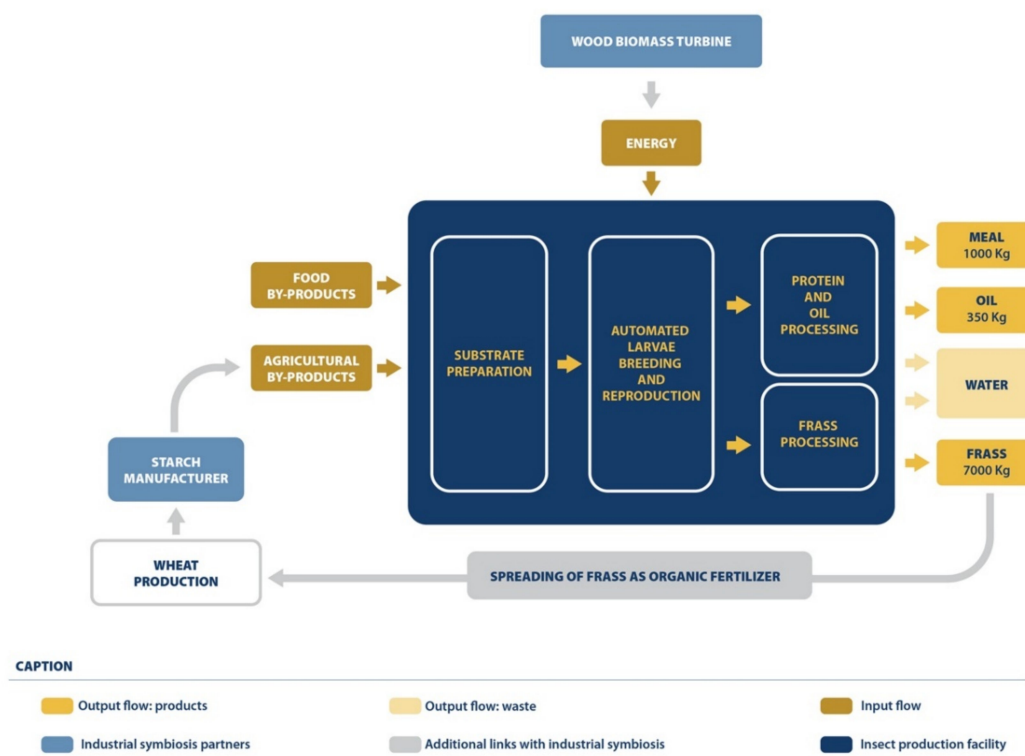


Figure 1. Inventory flows in the symbiosis model.

Similarly, the location of the insect production facility close to the wood biomass turbine of the renewable energy power plant enabled capturing the turbine's waste energy (i.e., energy that was previously dissipated in the atmosphere) in the form of water at 60 °C; the calorific capacity of this heated water was extracted at the insect production facility before the water was sent back to the turbine to be heated again. This waste energy corresponded to 53% of the production facility's energy need. The remaining 47% was sourced from the nearby energy power plant, consisting solely in renewable energy in the form of steam (8 bar, 29% of total consumption), and electricity (18% of total consumption).

2.2.2. Scenario Analysis

The environmental performance of the symbiosis model was compared to that of the no-symbiosis model (Figure 2) assuming the following scenario:

- Agricultural by-products were sourced dry ($DM_{\text{slurry}} = 88\%$, $DM_{\text{bran}} = 88\%$) from a starch manufacturer located 40 km away and transported by truck;
- Hence, additional water was required to mix the agricultural by-products and obtain a BSFL feed substrate with the same DM content as in the symbiosis model;
- Electricity was sourced from the French grid (standard renewable energy to fossil resources ratio);
- Heat was sourced from a gas furnace instead of using waste energy, steam, and warm slurry as in the symbiosis model.

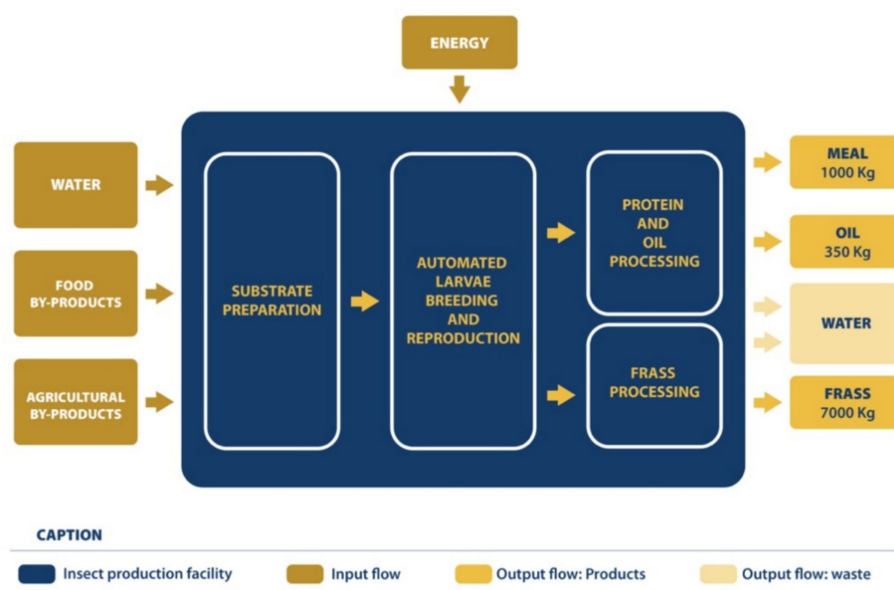


Figure 2. Inventory flows in the no-symbiosis model.

Feed and energy needs were assumed equal between models including larvae feed conversion ratio (FCR), substrate composition and total DM content, and total energy needs (in GWh/FU). Output flows including IM, IO, frass, and water were also assumed equal between models.

2.3. Impact Assessment (ISO 14044)

2.3.1. Methodology and Indicators

The assessment followed the standard A-LCA approach (ISO 14040, 2006; ISO 14044, 2006) using the SimaPro software (<https://simapro.com>). Three mid-point life cycle indicators were considered according to the IMPACT 2002+ methodology [16]: Climate change, fossil resources depletion, and land use. Economic allocation was applied to distribute the environmental impact across inputs (wheat bran and wheat slurry, as well as food by-products) and outputs (IM, IO, and frass).

2.3.2. Environmental Impact Calculation

For the no-symbiosis model, impact factors were sourced from Agribalyse 1.3, as implemented in SimaPro. In the symbiosis model, impact factors for wheat bran and wheat slurry inputs, as well as for the electricity input, were adapted to account for the specificities of the model:

- The impact of wheat slurry was adjusted to consider the cancelation of the drying step of the process as wheat slurry was supplied wet (15% DM) in the symbiosis model;

- The impact of electricity was adjusted to account for the use of at least 80% wood waste in the wood biomass turbine, as required by CREII certification;
- No impact was associated with the waste energy and heat captured from the wheat slurry nor with the transport of starch by-products in the symbiosis model as the latter are conveyed between partners through a direct pipeline;
- Finally, for wheat bran and wheat slurry, the replacement of nitrogen-phosphorous-potassium (NPK) mineral fertilizers by insect frass considered the NPK profile of the frass as well as the wheat NPK intake from mineral sources necessary for its growth. Based on the NPK required to produce the wheat by-products and on the NPK content of the produced frass, it was assumed that the latter could replace 100% of the NPK fertilizer required to produce the wheat by-products used as BSFL feed. This was the only consequential effect considered in this A-LCA.

2.4. Sensitivity Analysis

A sensitivity analysis was performed to assess if the environmental impact of BSFL production using the industrial symbiosis model could be further improved. This analysis tested the impact of improving larvae FCR. Given that insect feeding is the largest contributor to the environmental impact of insect rearing, improving larvae FCR might reduce the intake of the raw materials required for production. As so, BSFL feed intake was reduced by 2%, 5%, and 10% without changing the proportion of the feed components.

3. Results

3.1. Environmental Impacts of the Symbiosis Model

In the symbiosis model, the environmental impact of producing each FU (1 t IM + 0.35 t IO + 7 t frass) was estimated as 944 kg of CO₂ eq emitted, 17 GJ of fossil resources depleted, and 2179 m².yr of arable land occupied (Figure 3). Feeding BSFL was the main driver of the environmental impact of the symbiosis model across all three indicators studied (91% for climate change, 94% for fossil resources depletion, and 96% for land use). The environmental impact of the energy used for each of the different production steps, i.e., feed preparation, growth and reproduction, IM and IO processing, and frass processing, was further estimated. Growth and reproduction accounted for 47% of the overall environmental impact of energy used across all three indicators.

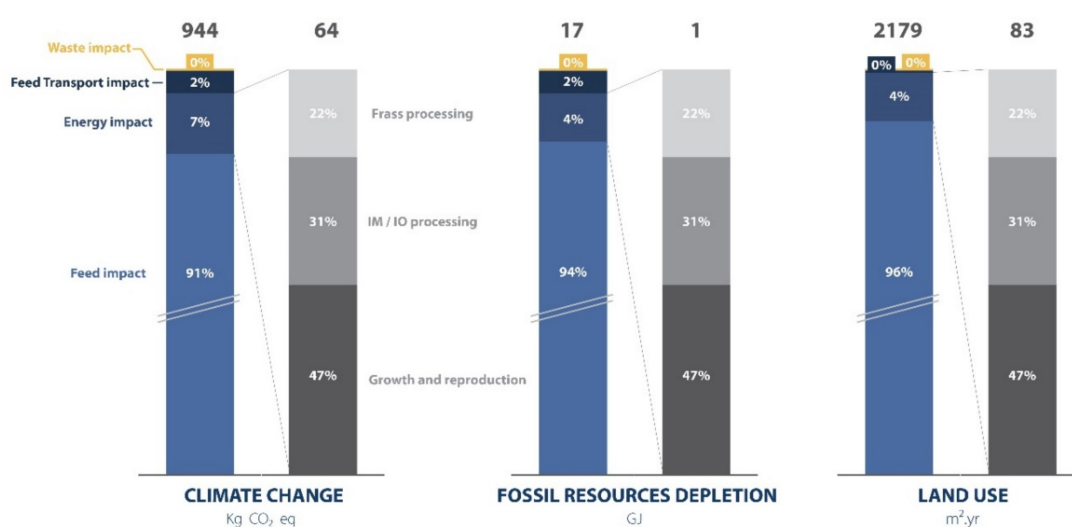


Figure 3. Breakdown of the environmental impact of each inventory flow (blue bars) and deep dive on the energy impact broken down across the different production steps (grey bars) of the symbiosis model.

3.2. Comparison of the Environmental Impacts of the Symbiosis and No-Symbiosis Models

The environmental impact of the symbiosis model was 80% and 83% lower than that of the no-symbiosis model considering climate change and fossil resources depletion, respectively, while the impact of land use was 3% higher. These differences are attributable to the four main differences between the two production models (Figure 4):

1. **The use of wet agricultural by-products:** In the symbiosis model, wheat slurry is received at 15% DM whereas in the no-symbiosis model it is dried up and received at 88% DM;
2. **The direct supply of by-products:** In the symbiosis model, wheat bran and wheat slurry are directly delivered from the starch manufacturer to the insect production facility through a pipeline whereas in the no-symbiosis model the same by-products are transported by truck over a 40 km distance;
3. **Energy mix optimization:** In the symbiosis model, the energy required to power the insect production facility is sourced from (i) the calorific capacity of the wheat slurry received at 80 °C, (ii) the calorific capacity of the water heated to 60 °C using the waste energy from the nearby wood biomass turbine, and (iii) the nearby wood biomass turbine itself; in the no-symbiosis model, the energy required to power the insect production facility is sourced from natural gas and electricity assuming the standard mix used in the French grid;
4. **The use of frass as fertilizer:** In the symbiosis model, the produced frass is assumed to be spread on agricultural lands thereby replacing 100% of the required mineral fertilizers to produce wheat bran and wheat slurry (the only consequential effect taken into account in this A-LCA); in the no-symbiosis model, no consequential effect related to the use of the produced frass was accounted for.

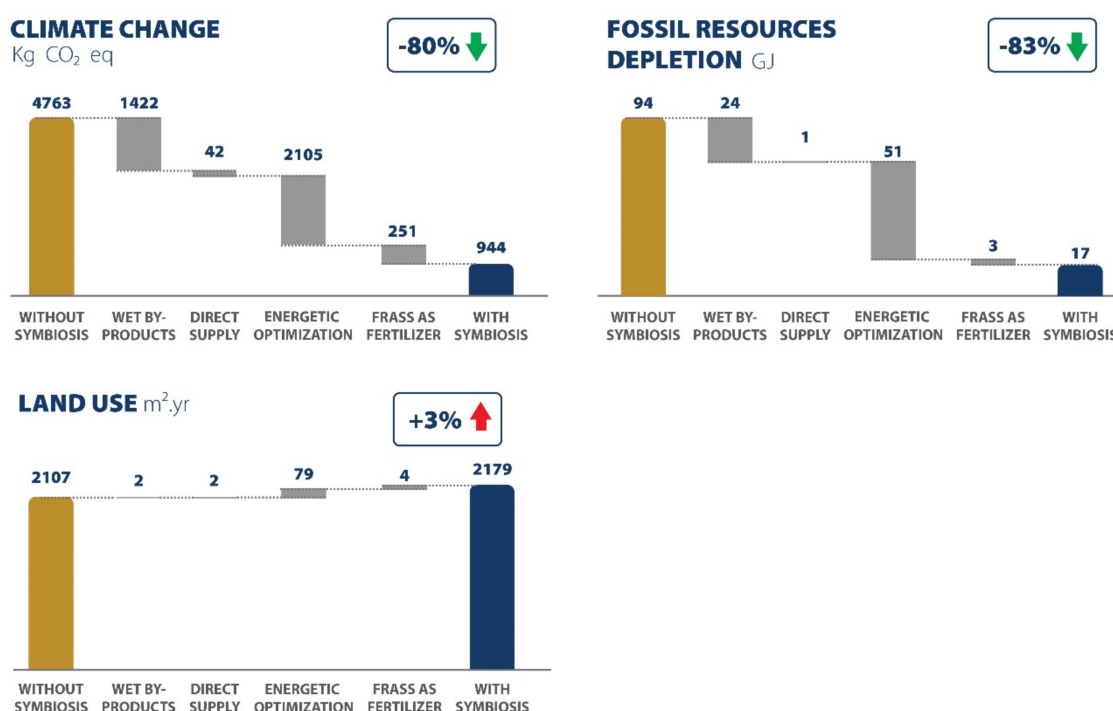


Figure 4. Comparative environmental impact of the symbiosis (blue bar) and no-symbiosis (yellow bar) models across the three indicators studied. The impact difference between models is broken down across each technological development implemented in the symbiosis model (grey bars).

Overall, the comparative analysis demonstrated that the use of wet by-products and optimization of the energy mix accounted for the larger proportion of the reduction in the environmental impact of

the symbiosis model regarding climate change and fossil resources depletion [1422 kg CO₂ eq (30%) and 24 GJ (25%) reduction for the use of wet by-products; 2105 kg CO₂ eq (44%) and 51 GJ (54%) reduction for energy optimization; Figure 4].

In fact, the technology developed and implemented in the symbiosis model, which enabled capturing waste energy from the wood turbine and reducing energy requirement due to using wheat slurry at 80 °C, accounted for the majority of the reduction in climate change attributed to the energetic optimization (1533 kg CO₂ eq or 73%). The remaining of the reduction in CO₂ emissions attributed to energy optimization (572 kg CO₂ eq or 27%) stems from the use of renewable energy from the wood turbine as opposed to the French standard electricity and gas in the no-symbiosis model.

However, the use of wood biomass energy in the symbiosis model increased the impact on land use by 79 m².yr compared to the no-symbiosis model (Figure 4). This marginal increase of 3% is due to using wood resources to power the turbine, despite its CREII certification guarantee that at least 80% of the wood burnt is waste wood.

Finally, the replacement of mineral fertilizers by insect frass in the symbiosis model only marginally reduced the environmental impact of this model regarding climate change and fossil resources depletion (251 kg CO₂ eq or 5% and 3 GJ or 3%, respectively; Figure 4); yet, this step allowed closing the loop for the circularity of the model.

The split of the environmental impacts across the production steps also differed between models (Figure 5). Considering the climate change and fossil resources depletion indicators, the impacts of feed preparation and larvae growth and reproduction were more evenly distributed in the no-symbiosis model (55% and 33% for climate change and 46% and 37% for fossil resources depletion, respectively), while in the symbiosis model the impact of feed preparation step accounted for more than 90% (93% for climate change and 96% for fossil resources depletion).

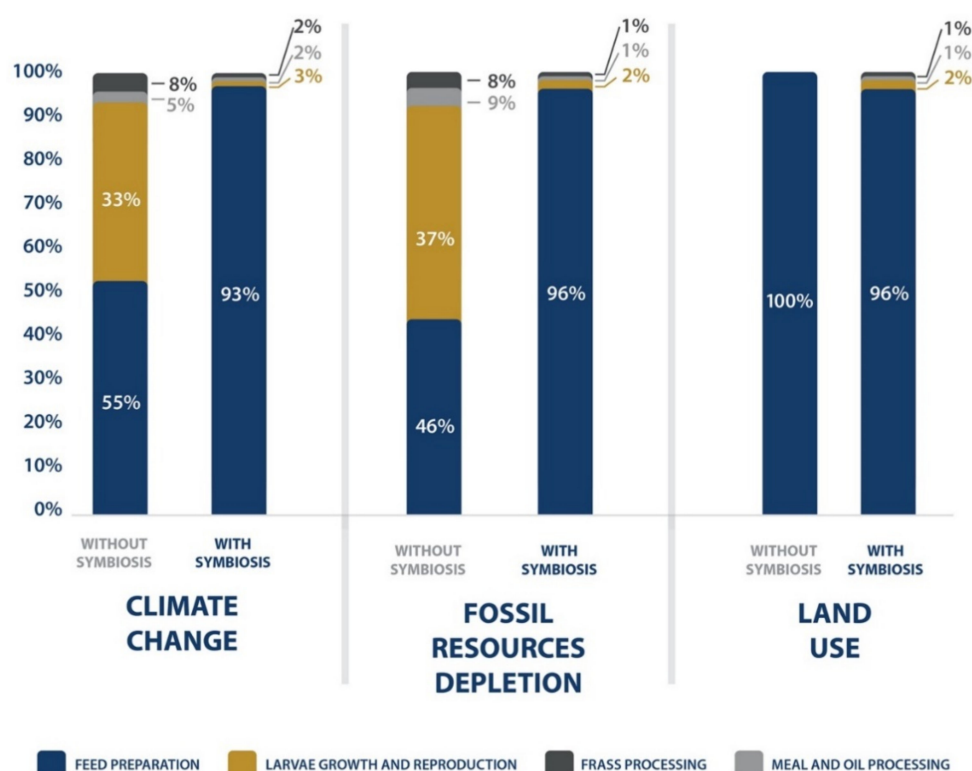


Figure 5. Breakdown of the environmental impact of each manufacturing step in the symbiosis and no-symbiosis models.

As for the environmental impact of each component of the FU (Table 1), i.e., IM, IO and frass, IM was attributed the largest impact share across all three indicators based on the economic allocation. This trend was maintained when the impact was calculated for each ton of product.

Table 1. Environmental impact of each fraction of the functional unit and of each ton of insect product.

	Climate Change	Fossil Resources Depletion	Land Use
	kg CO ₂ eq	GJ	m ² .yr
Total of functional unit	944	17	2179
<i>Per fraction of the functional unit</i>			
IM (1 t)	57%	86%	86%
IO (0.35 t)	8%	12%	12%
Frass (7 t)	35%	1%	1%
<i>Per ton of insect product</i>			
IM (1 t)	536	9.39	1239
IO (1 t)	218	3.81	503
Frass (1 t)	47	0.02	2.59

3.3. Comparison of the Environmental Impacts of IM and IO with Their Alternatives

3.3.1. Comparison of IM and FM

For the comparison of IM and FM, 1 t of IM was considered nutritionally equivalent to 1.03 t of FM to account for the FCR reduction resulting from the replacement of FM with IM and for the difference in crude protein content (FM = 70%; IM = 65%). For this comparison, a fish basket representative of the most likely applications of IM in aquaculture was used (50% salmon + 10% trout + 40% shrimp). Two types of FM included in the Agribalyse 1.3 database were used for the comparison to consider the different FMs available in the market: FM from anchovies from Peru and FM from Blue Whiting from Norway. Using 1 t of IM instead of 1.03 t of FM resulted in 55–75% reduction of CO₂ emissions and 46–70% reduction of fossil resources depletion (Figure 6). As expected, IM production had a land use impact higher than that of FM, as the BSFL were fed on agricultural by-products whereas wild fish diet was not accounted for in the A-LCA.

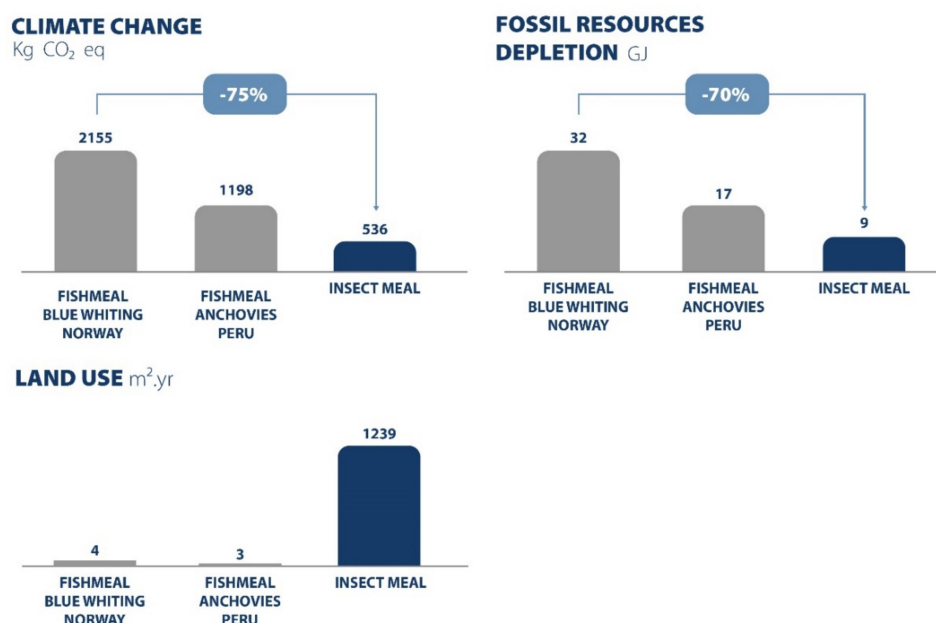


Figure 6. Environmental impact of producing insect meal and fishmeal as feed ingredients for a fish basket composed of 50% salmon, 10% trout, and 40% shrimp.

3.3.2. Comparison of IO and VO

For the comparison of IO and VOs, particularly coprah and soy oils, 1 t of IO was considered nutritionally equivalent to 1 t of soy and coprah oils included in swine and poultry feed. To account for the traceability of the soy oil, two types (with and without deforestation) were retrieved from the Agribalyse 1.3 database and used for the comparison. Producing 1 t of IO compared to producing of 1 t of VOs showed an overall improvement of the environmental impact across all indicators: 83–95% reduction of CO₂ emissions, 77–91% reduction of fossil resources depletion, and 87–96% reduction in land use (Figure 7). These reductions were mostly driven by vertical insect farming, which uses limited space, and by the symbiosis of the three industries in which the waste of one is used as raw material for another.

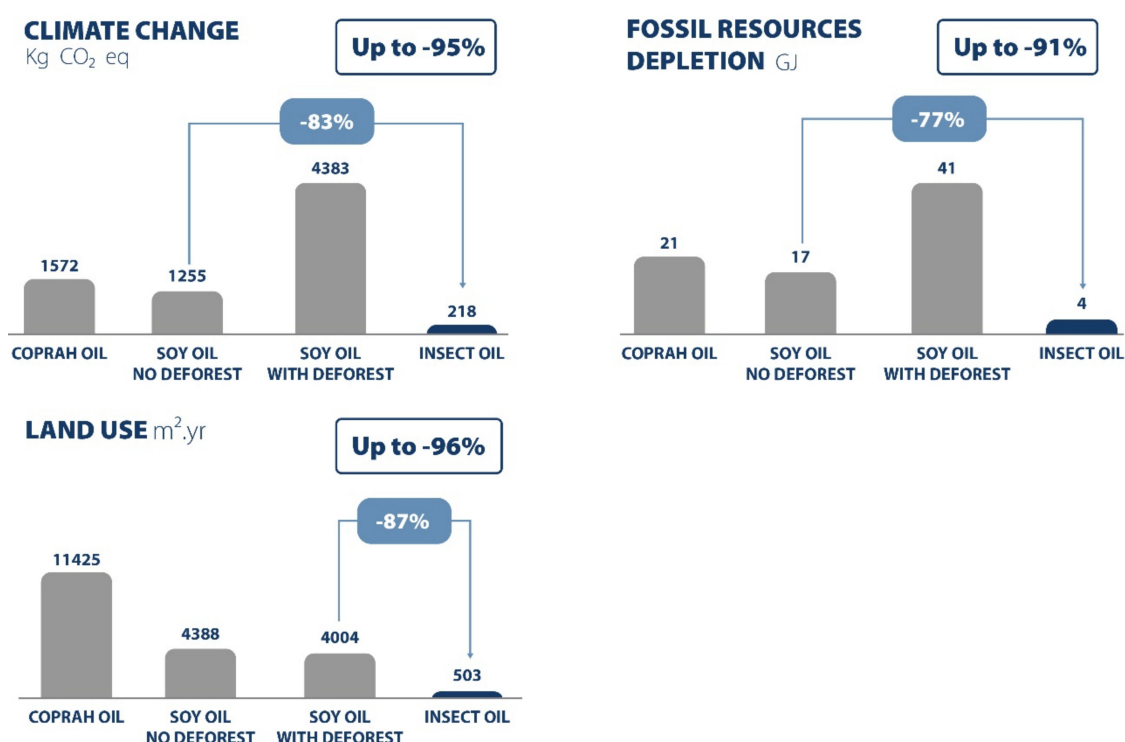


Figure 7. Environmental impact of producing insect oil, coprah oil, and soy oil, with and without deforestation, as feed ingredients for swine and poultry.

3.4. Sensitivity Analysis

Agricultural by-products required to feed the larvae were by far the inventory flow with the largest environmental impact across all three indicators. The sensitivity analysis performed to verify if the reduction of BSFL feed intake could improve the environmental impact of insect production revealed that a reduction of BSFL feed intake to 90% resulted in a proportional reduction (~10%) in the environmental impact across all indicators (Table 2).

Table 2. Environmental impact of feed reduction during BSFL rearing.

Environmental Impact Indicator	Feed Intake		Environmental Impact Reduction
	100%	90%	
Climate change (kg CO ₂ eq)	944	856	9%
Fossil resources depletion (GJ)	17	15	10%
Land use (m ² .yr)	2179	1969	10%

4. Discussion

4.1. Impact of the Innovative Symbiosis Model Compared to That of the No-Symbiosis Model

This study contributed new data to the improvement of the environmental impact and sustainability of large-scale insect production by analyzing an industrial symbiosis model. The LCA results demonstrated that this symbiosis model is a game changer for the sustainability of industrial insect production with 80% reduction in CO₂ emissions (57 kt of CO₂ eq saved per year on the plant or 3.8 t of CO₂ eq saved per FU) and 83% reduction of fossil resources depletion (1170 TJ per year, which is equivalent to ~200,000 oil barrels) when compared to the no-symbiosis model. This symbiosis model addresses the key limitations previously acknowledged for the environmental sustainability of insect production, i.e., the input of raw materials for feeding insects and energy consumption. By using warm and wet agricultural by-products (wet wheat slurry) that are delivered via a pipeline linked to the starch manufacturer partner, the symbiosis model allowed (i) saving the drying energy and water that would otherwise need to be added to the substrate, (ii) reducing the greenhouse gases emissions associated with the transportation of the agricultural by-products and (iii) reducing the total energy needs of the production plant by capturing the calorific capacity of warm slurry. This first particularity of the symbiosis model resulted in saving 1422 kg CO₂ eq and 24 GJ per FU compared to the no-symbiosis model. Furthermore, the symbiosis model also enabled (i) using waste energy previously released to the atmosphere to heat the insect rearing facility (accounting for 53% of total energy consumption) and (ii) powering the entire insect production facility with renewable energy from a wood-based co-generated energy plant located next to it. This, in turn, resulted in a reduction of 2105 kg CO₂ eq and 51 GJ per FU, when compared to the no-symbiosis model.

Although the symbiosis model slightly underperformed compared to the no-symbiosis model in terms of land use (marginal increase of 3%), this was due to the forestry that is required to provide wood for the co-generation unit, as 20% of such wood is not waste wood (increase of 79 m².yr per FU). Hence, and depending on the category of environmental impact assessed, using wood-based co-generation is simultaneously responsible for the better and worse performances of the symbiosis model, highlighting the importance of a multiple impact analysis.

Several studies have confirmed IM and IO as reliable alternative ingredients to FM and VO (soybean oil in most assessments), respectively, particularly regarding the nutritional demands and zootechnical performance of terrestrial and aquatic species e.g., [5–10,17]. In addition, insects have been acknowledged as sustainable sources of protein and oil [13–15,18–20]. Comparing the present results for the three indicators with those of previous LCAs, the lowest environmental impact values obtained for the symbiosis model are notable, regardless of insect species and production models (Table 3).

Table 3. Comparison of the environmental impact of producing 1 t IM using different insect species and production models.

Insect Species [Reference Source]	Indicators		
	Climate Change kg CO ₂ eq	Fossil Resources Depletion GJ	Land Use m ² .yr
House fly larvae [21]	770	9.3	32
House fly larvae [22]	-	159.8–288.1	2790–5320
Mealworm larvae [23]	3500	44.3	4680
Mealworm larvae [24]	7100–7550	80.0–101.0	50
BSFL [25]	-	13.4–64.06	10–40
BSFL [26]	1240	1.5	-
BSFL [13]	2100	15.1	50
BSFL [18]	1360–15,100	21.2–99.6	32–7030
BSFL [present study]	536	9.4	1239

Although in terms of climate change and fossil resources depletion (536 vs. 770 kg CO₂ eq, 9.4 vs. 9.3 GJ, respectively) the results of the present study are similar to those for house fly larvae in the work

of Van Zanten et al. [21], the data used by these authors were not obtained from a production unit, as it is the case of the present study, but from a hypothetical scenario extrapolated from research data results. The large difference in land use is easily explained by the exclusive use of pre-consumer food waste as larvae feeding material in the study by van Zanten et al. [21], which is difficult to rely on for large scale production of IM (further discussed below).

4.2. Impact Drivers and Scope for Improvement in the Symbiosis Model

The results obtained in the present A-LCA indicate that the largest contributing factor across all environmental impact indicators was insect feeding on wheat bran and wheat slurry (91%, 94%, and 96% of the total impact for climate change, fossil fuels depletion, and land use, respectively). The use of energy, particularly in the growth and reproduction phase, also contributed to the overall impact of the production process but to a much lower extent. These results agree with those of previous LCA studies; for example, the environmental impacts of larvae feeding and energy use were 55% and 38%, respectively, in Smetana et al., 2019 [15] and 75–80% and 15–19% in Smetana et al., 2016 [18].

The higher impact from feed in the present study results from the usage of agricultural by-products, whereas the use of renewable energy drastically reduced the impact of energy use on the overall results. In contrast, the no-symbiosis model, energy consumption resulted in a substantial fraction of the climate change impact and fossil resources depletion accounting for respectively ~45% and ~54%. Smetana et al. [15] highlighted energy consumption as a major area for improvement that would enable decreasing the total impact of insect production by 25% just by switching to renewable energy sources. However, the authors foresaw this change as a long-term transition (10 years) due to the need of considerable investments. The results of the present study clearly demonstrate that co-locating insect plants with existing industrial players can accelerate this transition and lower the impact of energy consumption at the onset of insects' industrial production.

As for the environmental impact of raw materials, two impact sub-drivers are to be considered: The type of feed material used and the FCR of such materials by the insects. As discussed in previous studies, BSFL is a promising biomass transformer capable of consuming feed streams that are not suitable for other livestock [27]. Smetana et al. [18] assessed the impacts of feeding BSFL on different diets (base scenario with rye meal and wheat bran compared to 13 feeding variations of by-products and waste streams) and concluded that using low-value food processing by-products (distilled grains), as the ones used in the present study, was among the best strategies for sustainable feed production. To further improve the sustainability of insect-based feed ingredients, multiple authors have stated that the use of consumer food waste or manure (to which no environmental impact is allocated) could be beneficial to increase the sustainability of the production process [22,23,28–32]. However, relying on such streams as insect feed is illegal in some regions (e.g., manure is not allowed as insect feed in Europe). Moreover, it represents a challenge for large-scale production due to fluctuations in their availability and to variability in their composition and quality. Finding adequate by-products, with nutritional quality for insects and low environmental impact, will therefore be of strategic importance in the emergence of the insect production industry. The present study suggests that, in addition to the type of by-product selected as insect feed, the way to supply it also enables saving energy and significantly reducing the environmental impact of feed drying and transportation, as evidenced by the use of the direct pipeline, only possible due to the co-location of the insect production facility and starch manufacturer partner.

Larvae FCR is another impact driver with scope for improvement. The sensitivity analysis conducted on larvae feed intake reduction showed that changes in environmental impact were directly proportional to changes in FCR (10% decrease in feed intake led to 9–10% decrease in the impact values of all three indicators). The FCR of BSFL is significantly lower than that of other insects, being the main reason for most insect producers choosing this species. In fact, the FCR for BSFL was almost half the 2.2 kg/kg of live weight value obtained by Oonincx & de Boer [23] (data not shown), suggesting that the FCR of BSFL can be further optimized through the better stability of production systems [15]

as well as by improving feed formulation, rearing conditions, and insect genetics thus improving the overall sustainability of insect-based ingredients' production.

Another area for improvement would be to increase the percentage of waste wood (the assumption used in the A-LCA was a waste wood minimum requirement of 80%) or biogas from bio-waste methanization in the mix used for energy generation to decrease land use without increasing the impact values of the other indicators.

4.3. Impact of IM and IO Compared to That of Conventional Feed Ingredients

Most previous studies on the environmental impact of insect production were conducted at laboratory or pilot industry scales, therefore hindering comparisons with the impacts of producing the conventional protein and oil sources, which occur at industrial scale. Moreover, most previous studies were based on partial or aggregated data, and not on data from a fully operational production facility. The present study, which is based on data from one of the first industrial scale insect production facilities worldwide, provides a basis for evaluating the environmental impact of novel insect-based ingredients (IM and IO) versus the conventional feed ingredients (FM and VOs) they can replace in aqua and monogastric feeds. The results of the present study confirmed the potential of IM and IO produced at industrial-scale as more sustainable than FM and VOs as suggested in previous small-scale studies [13–15,18–20]. Overall, replacing FM by the IM produced using the industrial symbiosis model can potentially decrease CO₂ emissions by 24 kt and fossil resources depletion by 336 TJ per year of operation of the insect production facility, which represent reductions by three- to four-fold. In addition, compared to the best alternative (soy oil without deforestation), IO production using the symbiosis model allowed saving 5.2 kt of CO₂ emissions, 64 TJ of fossil resources, and 1900 ha of land use per year of operation. Nevertheless, the better environmental performance of the IM and IO demonstrated here applies only to the ingredients produced using the symbiosis model and therefore cannot be generalized to all models of insect production at large-scale.

Although the A-LCA presented here provides a solid basis for comparing insect-based feed ingredients with conventional feed ingredients, there are some limitations. First, the lack of methodologic standards to assess the environmental impact of ingredients means that results from different studies are not directly comparable. Second, the FU selected for comparison will depend on the species the insect-based feed is intended for as well as on the specific formulation used by each market player. Finally, assessing the impacts of FM production on marine biodiversity, which were not included in the present assessment, would require an evolution in LCA to account for the threats to marine ecosystems [33].

5. Conclusions

This A-LCA of one of the first industrial-scale insect production facility in operation in the world demonstrates that the innovative symbiosis model implemented on the site drastically reduces the climate change and fossil resources impact of the production of insect ingredients. The symbiosis model which consists in the colocation of the insect facility with a feed manufacturer to directly supply by-products to feed the larvae and a renewable power plant to valorize waste energy to power the plant reduces CO₂ emissions by 80% and fossil resources depletion by 83% compared to a no-symbiosis model. This study further displays the precise environmental impact of IM and IO using the symbiosis model across climate change, fossil resources depletion and land use. The comparison of these results to the ones of alternatives (FM for IM and VOs for IO) demonstrates that IM and IO are both sustainable alternatives reducing CO₂ emissions by at least 51% and fossil resources depletion by 46%. However, these reductions in environmental footprint are only achieved when using a symbiosis model therefore outlining the importance of performing LCA to demonstrate the sustainability of other production models at industrial scale.

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