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# Comparative Life Cycle Assessment of Insect Meal Production in a United States Cold Climate Region for Fishmeal Alternatives

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**Abstract**

Aquafeed is one of the most environmentally impactful inputs to the aquaculture industry—an industry that is growing and is projected to grow for the foreseeable future. Of the ingredients of a typical aquafeed, fish meal and oil have the greatest environmental impact for many categories. Conventional fishmeal and oil are produced using wild-caught, prey fish and many are already being harvested up to the threshold where the remaining population would decline further if more were harvested. For these reasons, fishmeal alternatives are necessary to aid the growth of the aquaculture industry, while also aiming to improve the environmental sustainability of the industry. The purpose of this study was to conduct a comparable life cycle assessment of three types of insect meal (i.e., black soldier fly larvae, house cricket, and darkling beetle larvae) using previously published inventories and additional assumptions to determine the viability of the meals as an alternative to conventional fishmeal from an environmental impact standpoint in a United States cold climate region. The assessment also included the biotic resource use impact category to generate a more complete view of the environmental impacts given most prior studies on the topic of fishmeal and its promising alternatives do not consider this vital impact. According to the results of the life cycle assessment, cricket meal is the least environmentally impactful in the most categories when compared to the other two types of insect meal, though black soldier fly larvae meal is the least environmentally impactful in four of the other categories. The results illustrate the promise of insect meal; however, in cold climates especially, optimizing efficiencies is imperative to reduce overall environmental effects due to high temperature and humidity requirements. Based on the study, insect meals are not yet a viable alternative to conventional fishmeal when only considering conventional environmental impact categories (e.g., global warming, acidification, and eutrophication potentials). When considering biotic resource use, insect meals are an order of magnitude less impactful, making it potentially viable if improvements are made to the production process. Improvements would mainly take place in the farming processes; however, utilizing renewable energy in all steps would greatly decrease many environmental impacts. Reducing space for the farming of the insects, selecting by-products or waste products for the feed, and exploring stocking densities are changes that would also improve the environmental impact of insect farming.

**Keywords:** insect meal; black soldier fly larvae; cricket; mealworm; aquaculture; fishmeal; life cycle assessment

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## 1. Introduction

Aquaculture is one of the fastest growing industries in the United States (US) today, generating billions of dollars in revenue, and is projected to continue to grow for the foreseeable future. Aquaculture is also currently the most common method for farming aquatic organisms globally, namely propagating fish such as tilapia and salmon [1]. This farming method is highly beneficial for reliably producing quality sources of protein and fat to the Anthropocene, while also alleviating some market pressure placed on select wild aquatic stocks by industrial fisheries [2–4]. While aquaculture has several benefits, its negative consequences force further investigation to develop more sustainable system characteristics.

One of the most environmentally impactful attributes of any aquaculture system is the aquafeed [5,6]. Conventional aquafeeds, along with many other animal feeds, contain fishmeal (FM) and fish oil (FO) as sources for protein, lipids, and omega-3 fatty acids [4]. Currently, FM and FO are sourced from wild-caught prey or forage fish such as sardines, menhaden, and mackerel, which is an issue both for the growing aquaculture industry and the wild organisms who depend on that food source, given most wild populations are already at their maximum sustainable yields [4,7,8]. Because of this constraint, alternative protein and lipid sources are vital in maintaining nutrient compositions in aquafeeds for the growing aquaculture industry.

Several different options for FM and FO alternatives show promise such as vegetable-, insect-, microalgae-, and aquaculture byproduct-based meals and oils [5] . Insects are specifically a favorable potential source of protein for animal farming as they typically have short life cycles, can be fed waste streams, are similar in protein content to FM, and require minimal processing for feed [9,10]. Figure 1 displays the inputs and outputs of a generalized insect farming system, though some species are harvested later in the life cycle of the insect and require other inputs such as pumpkin (for the color of the final product) or a cleaning solution for maintaining good hygiene between cycles. In Figure 1, the solid boxes refer to the typical farming cycle of insect propagation and processing, the blue dashed boxes refer to the inputs required for each step in the farming and processing operations, the green box denotes the waste outputs, and the magenta dashed boxes refer to the desired outputs for this type of insect farming operation. Fatty acids can be extracted from insect biomass; however, omega-3 fatty acids (an essential nutrient for aquatic species) are generally limited in insects, requiring either supplements in the insect's feed source or in the final meal and oil products [11]. Though insects seem to be a viable alternative to FM and FO, assessment of their environmental impact is critical for ensuring these products are not more environmentally detrimental when compared to their antecedent.

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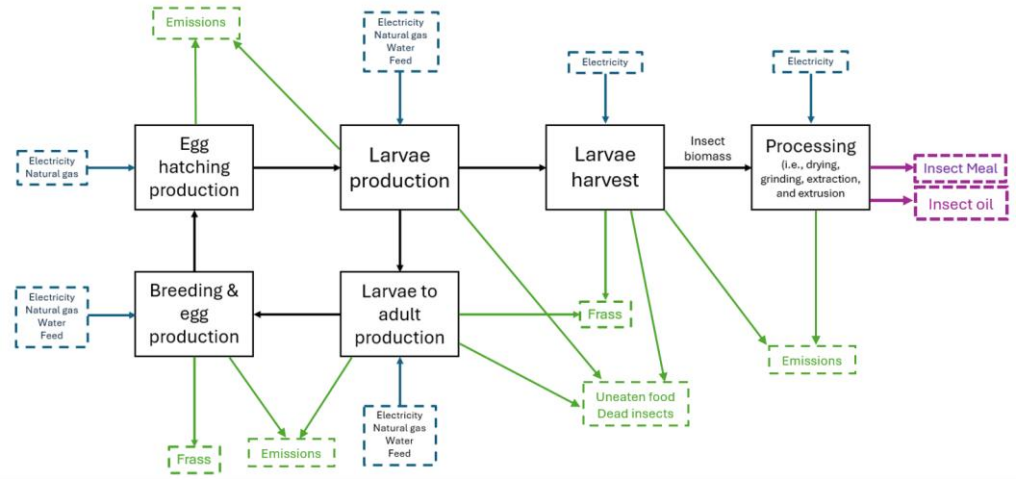


**Figure 1.** Generalized insect farming operation to produce meal; black, solid boxes are the production stages for producing insect meal; blue, dashed boxes denote inputs; dashed, green boxes represent system outputs; and magenta, dashed boxes signify desired outputs of this system.

Life cycle assessment (LCA) is a commonly utilized tool for quantifying the environmental burden of products and processes [12]. Environmental investigations of insect farming exist, though mainly from other countries across the world, since more residents consume and utilize insects and they are overall much less taboo in general, making insect farming more viable than the current US market. Since the industry is already beginning to develop in Europe, several LCA studies exist on several kinds of insects such as black soldier fly larvae (BSFL) and mealworms (i.e., darkling beetle larvae), which are fed a diet of either animal feeds, agricultural byproducts, or waste streams. [9] conducted an LCA study of BSFL in the Netherlands with scenarios for the use of standard feed diets and food industry side streams and found the assessed insect-based products to be competitive relative to greenhouse gas (GHG) emissions and land and energy use when compared to other meals. One vital consideration of animal farming in general is the concern of burden shifting within agriculture by using certain feed streams (e.g., wheat middlings and wheat starch slurry). Many food/feed side and waste streams are already fed to livestock or used as compost/ground cover for crop agriculture, meaning their food source is likely coming from an already saturated source, which is an important consideration given the potential of disruptions in other food and feed industries. Another study by [13] investigated the environmental impacts of the yellow mealworm in Austria. The authors found the electricity input, specifically the electric heater, generated the largest environmental impacts for mealworm production. They conclude that insect farming can compete environmentally with conventional animal farming; however, efficiency improvements and large-scale operations are necessary to truly be more environmentally sustainable than traditional animal products [13]. A relevant takeaway from the available literature on the environmental impacts of insect farming meals is the differences in reported impacts. Figure 2 presents the global warming potential (GWP) of several studies that investigated either BSFL (purple, dotted) or mealworms (green, striped). GWP calculates the total GHG emissions of a product or process and was selected given the calculation of this impact category is similar amongst life cycle impact assessment (LCIA) methodologies. As shown, there are major differences even amongst the same species for this one impact category. The differences in impact arise for a variety of reasons, one being the location of the operation or differences in the annual harvest quantities. Currently, no insect LCAs exist in the US and few commercial-scale farms are operating (about 50 total in North America), though interest is quickly rising [14,15].

One major consideration in the investigation of meal alternatives is the biotic resource use (BRU) of these products. BRU considers the quantity of biotic resources or living organisms required to produce the investigated product. Because conventional FM and FO rely almost entirely on wild-caught fish, which is a vital and limited biotic resource, it is critical that these alternatives patently reduce the amount of BRU required and/or that the biotic resources used are not from the same sources as conventional meals. Many LCAs of FM alternatives do not include the consideration of BRU, which is a more relevant impact category than many of the common ones in this application, making the story expressed by the assessment incomplete with respect to the ecosystem services provided by the oceans in producing FM and FO.

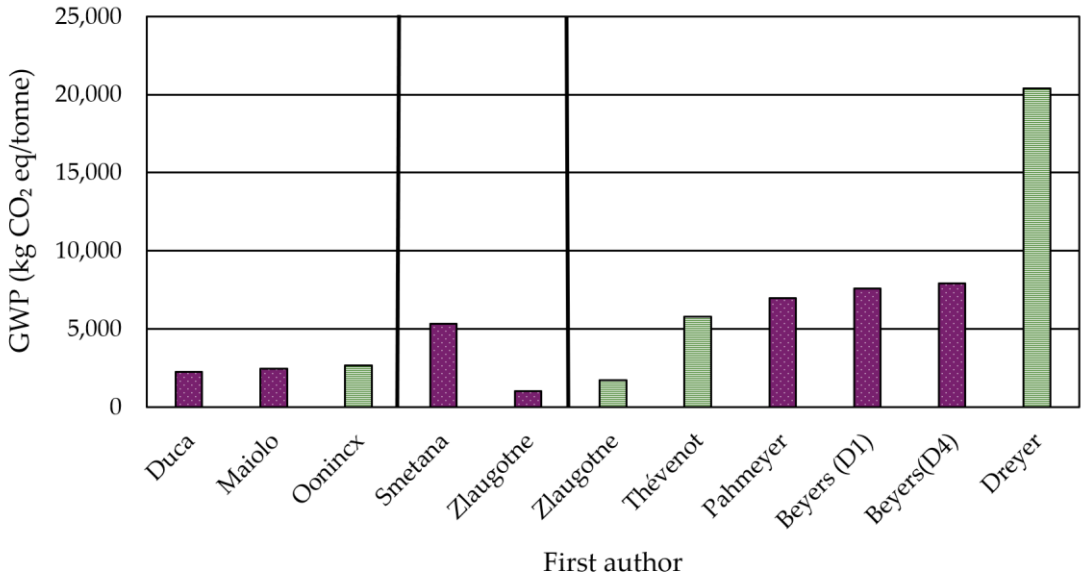


**Figure 2.** GWP of published LCAs for either one tonne of larvae or meal using BSFLs (**purple**) or mealworms (**green**); left section is per tonne of liveweight, middle section is per tonne of meal, and right section is per tonne of protein [9–11,13,16–20].

The goal of this work was to assess the environmental impacts of farming three different types of insects (i.e., BSFL, crickets, and beetle larvae) to generate insect meals in a cold climate in the US, specifically Madison, Wisconsin, which has a humid continental climate according to the Köppen–Geiger climate classification [21]. In this work, LCAs were conducted with the inclusion of BRU for the three investigated insects (biomass and protein content), which was then compared to conventional FM, microalgae-based meal, and vegetable-based meal from the literature to determine their viability relative to the environment for current and other promising meals.

## 2. Materials and Methods

In accordance with the International Standards Organization (ISO), LCA involves four main stages: the goal and scope definition, inventory collection, LCIA, and interpretation [12]. The impact methodology utilized in this assessment was the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), which determined the midpoint impact categories included in the assessment. To perform the LCA, SimaPro 10.3.0.4 software was utilized, which drew from ecoinvent 3, US Life Cycle Inventory (USLCI), and Agri-footprint 6 databases [22–24].

### *2.1. Goal and Scope Definition*

In the agricultural context, the most common environmentally impactful life cycle stages of many products are the raw materials acquisition and the production phases, so a cradle-to-processing gate system boundary for this theoretical production operation was chosen for the LCAs [25,26]. The cradle-to-processing gate considers the acquisition of the raw materials and processing required to produce the meal; however, waste streams (i.e., frass, uneaten food, and dead insects) were not included in the assessments for consistency amongst the assessments and due to limitations within the literature and available databases [9,10,27]. These waste streams could be used as an alternative fertilizer but would generally need further processing for optimal usage. The use phase was also specifically excluded as further experimentation would be required for the actual implementation of the insect meals relative to quantity and composition of the feed given the variability in nutrient composition which would depend on the insect's feed composition, so this phase was not included in the scope of this study. End-of-life was excluded as this phase would severely narrow the applicability of the LCA given the specificity of waste disposal locations, making the transportation required equally explicit. Two functional units (FUs) were selected for the assessment as one provides useful results for current and future insect farmers and the other provides results useful for feed and animal producers and were chosen to be one tonne (i.e., 1000 kg) of insect meal and one tonne of protein.

### *2.2. Data Sources and Inventory*

All utilized studies were translated into theoretical operations located in Madison, WI, USA, meaning supplemental heating is required to maintain environmental conditions during the farming process, dependent on the location of the original operations. The US cold climate is specifically noteworthy for investigation due to the increased dependence on energy (for heating). Five published insect farming inventories were the basis of the three LCAs conducted in this study, though some supplemental inventories and data were needed for completion [10,17,19,28,29]. Scales of operations amongst the three differed (BSFL: 109,000 kg/yr, cricket: 36,741 kg/yr, mealworm: 83,200 kg/yr). More details on the inventories can be found in the Supplementary Materials.

### *2.3. LCIA*

Following the US Environmental Protection Agency's protocol, TRACI 2.2 (V1.01) was utilized to characterize impact categories [30]. TRACI 2.2 contains the following impact categories and will be included in the results and Supplementary Materials: Acidification potential (AP, kg$SO_2$ eq), marine eutrophication potential (MEP kg N eq), freshwater eutrophication potential (FEP, kg P eq), global warming potential (GWP, kg $CO_2$ eq), smog formation (SF, kg $O_3$ eq), respiratory effects (RE, kg PM2.5 eq), ecotoxicity (EC, CTUe), ozone depletion (OD, kg CFC-11 eq), human health carcinogens (HHC, CTUh), and human health non-carcinogens (HHNC, CTUh) [30]. All impact categories were included in the assessment for completeness purposes, though not all categories are entirely relevant to this application. GWP, BRU, AP, and MEP were specifically included in the results and discussion sections. The remaining results can be found in the Supplementary Materials.

Due to the lack of consideration of biotic resources in most previously published LCAs, the impact category BRU (kg biotic C) was quantified in this LCA. Since alternative meals aim to mitigate the use of conventional FM, it is vitally important to have an impact category that takes the amount of biotic carbon required to produce the product into consideration. BRU methodology was initially coined by [31] and was adapted for this application. The methodology considers the trophic level of the desired product as well as the quantity of carbon-based resources required [31]. Put simply, BRU, which is the

summation of carbon required to produce the FU, is calculated. For FM and plant-based inputs, several published articles were utilized, though some carbon content was provided with the inventories used [10,32–39]. For palm oil, carbon content was determined using amino acid composition approximations and resulting calculations can be found in the Supplementary Materials.

Uncertainty was investigated for all impact categories, with the exception of BRU, as the data sources, assumptions, and decisions made in the LCA will inevitably lead to a degree of uncertainty. This uncertainty is specifically derived from the background datasets provided by the utilized databases. To do this, Monte Carlo simulations were conducted using the SimaPro 10.3.0.4 software where 1000 runs of the assessments were completed with 95% confidence. An uncertainty analysis for the BRU impact category could not be conducted, due to inadequate available distribution data; however, uncertainty relative to the impact category would arise from considerations such as limited available data, assumptions, and geospatial differences. Sensitivity analyses were also conducted to better understand which inputs impact the overall emissions the most by varying each input by 20%.

Given there are several inputs that are co- or byproducts of agricultural processes (i.e., wheat bran and rice husk)—as well as insect meal producing some oil, if defatted—it is necessary to also investigate impacts with allocation considerations. Several feed inputs such as wheat bran and rice husk are byproducts of other agricultural products and are therefore allocated on a mass or economic basis in the LCA, which is already executed in the utilized databases (the agri-footprint database uses economic allocation). The separation of insect meal and oil is an important process as different species of farmed animals require varying amounts of protein and lipids for optimized growth and allows feed producers to broaden their markets to virtually all artificial animal propagation operations. The set of results shown in the figures below does not allocate any environmental burden to the insect oil given the studies' focus on meal and the absence of essential nutrients such as omega-3, which can be found in FO. Results for a mass-based allocation for the meal and oil where the environmental burden is shared between the two products for all stages of production are provided in the Supplementary Materials. For the allocation considerations of the final products, BSFL produces 76.9% meal and 23.1% oil, while crickets produce 88.2% meal and 11.8% oil, and mealworm meal (MM) also produces 11.5% oil (88.5% meal) all on a mass basis [17,19,40].

## 3. Results

*LCIA, Uncertainty and Sensitivity Analyses*

Results for the four impact categories (GWP, BRU, AP, and MEP) are presented below, with the remaining impact categories being reported in the Supplementary Materials. GWP was selected for presentation given its prevalence in previous articles and its ability for harmonization with other LCIA methodologies, which is important for comparison [41]. BRU was also chosen for presentation given its usefulness in this application for giving a more complete story when compared to conventional fish meal. AP and MEP were selected given the use of harmful chemicals such as pesticides and synthetic fertilizers in producing the feed inputs. Figure 3 presents the LCA results for the GWP impact category for the three assessed insect meals, broken down by each input. The figure indicates that BSFL meal (BSFLM) is the lowest of the three insect meals mainly due to lower electricity usage and total feed quantity per tonne of meal.

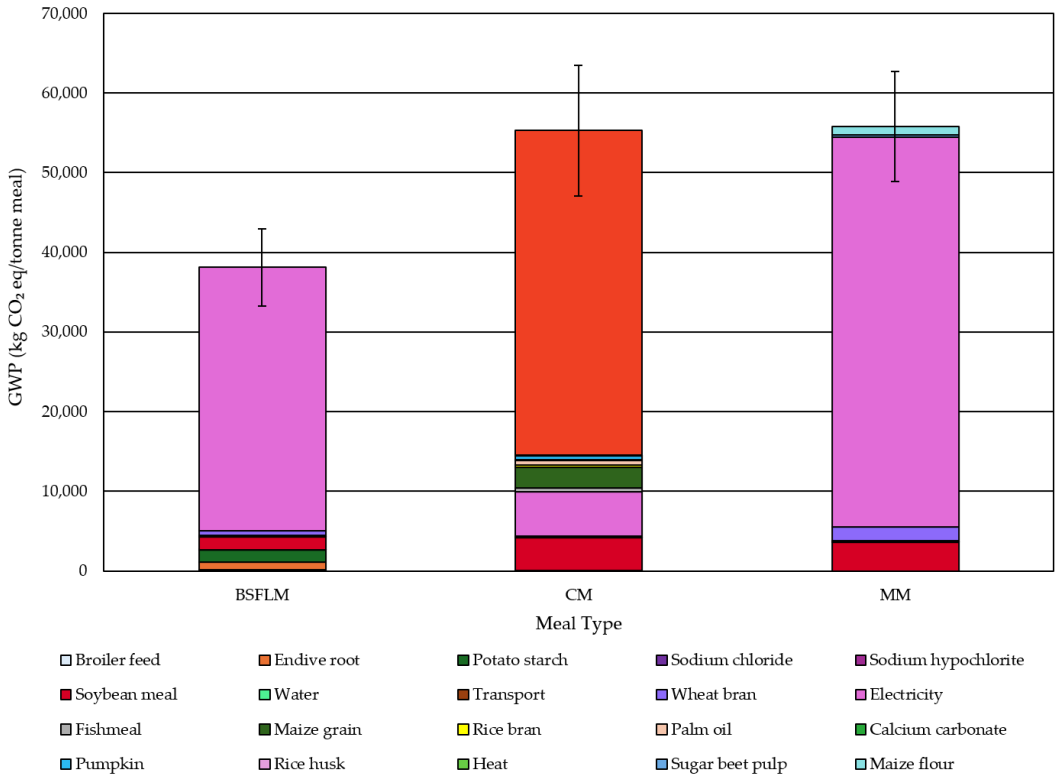


**Figure 3.** LCA results for GWP for one tonne of BSFLM, cricket meal (CM), and MM.

Figure 4 displays the LCA results for the BRU impact category for the three investigated insect meals broken down by inputs. The figure shows cricket meal (CM) as having the greatest impact relative to the other two, mainly due to the use and quantity of fishmeal and maize, with MM being the second most impactful mainly due to the use and quantity of wheat bran.

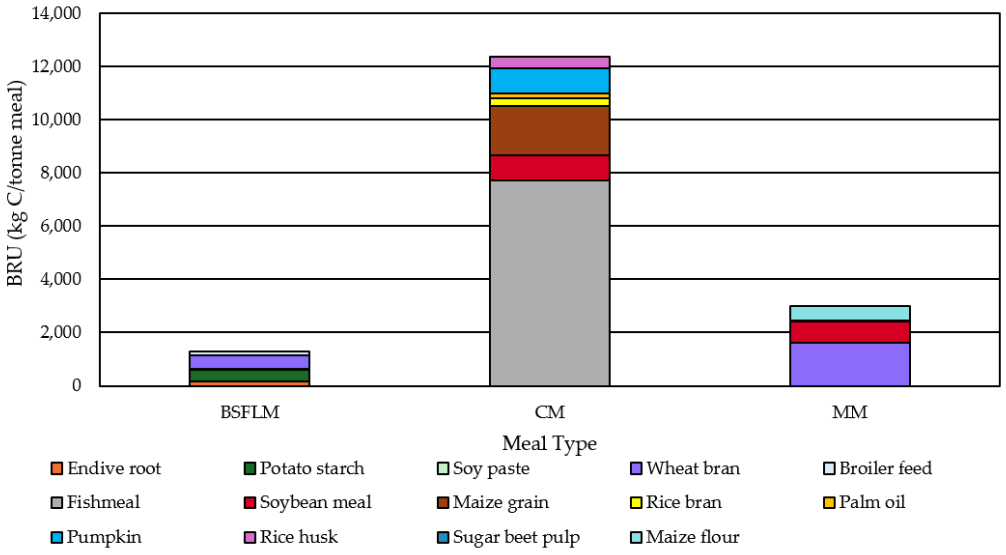


**Figure 4.** LCA results for BRU for one tonne of BSFLM, CM, and MM.

Figure 5 shows the results of the AP impact category for the assessed insect meals which are broken down by each assessment's inputs. The results for this impact category are relatively similar for the three meals, with MM being the most impactful and CM being

the least impactful. The main contributor to this impact category for BSFLM is electricity, endive root, and potato starch. For CM, the main contributor is heating, maize, and electricity, and that for MM is electricity and wheat bran for the AP impact category.

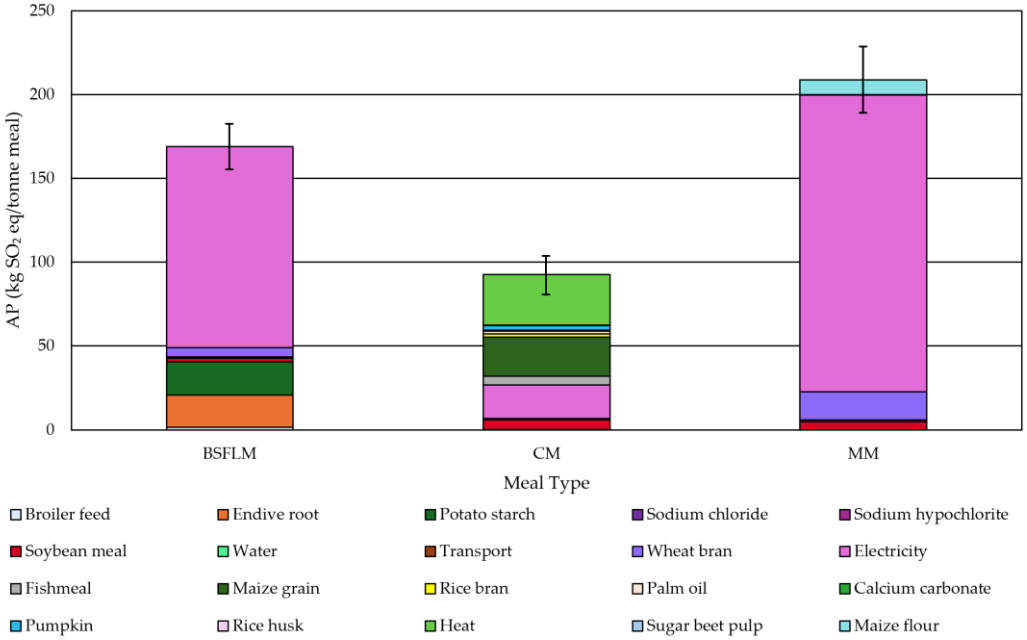


**Figure 5.** LCA results for AP for one tonne of BSFLM, CM, and MM.

Figure 6 expresses the results for the MEP impact category for the investigated insect meals. For this impact category, CM has the lowest impact, with MM being a close second. BSFLM has the highest impact mainly due to electricity, endive root, and potato starch.

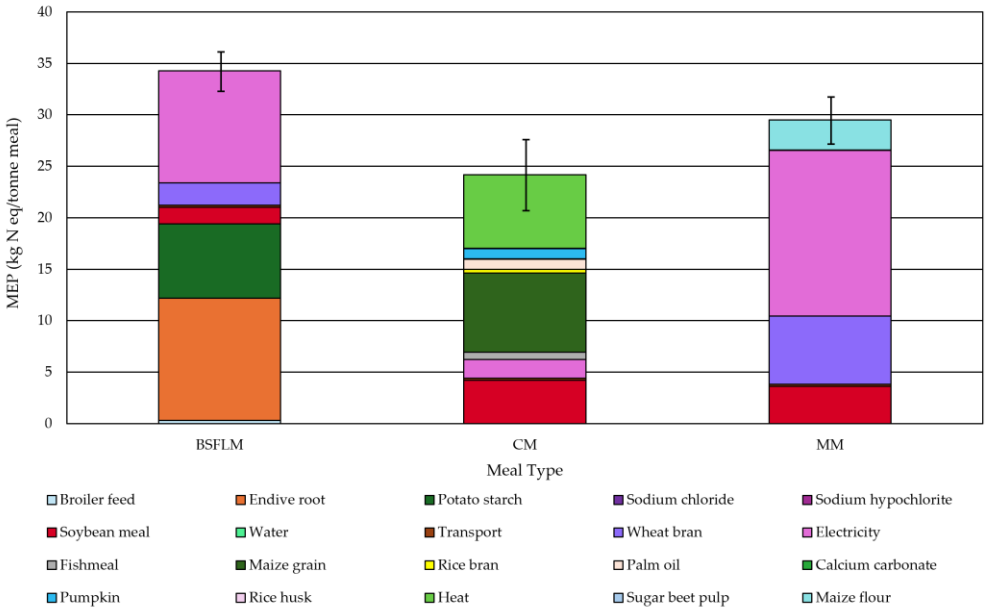


**Figure 6.** LCA results for MEP for one tonne of BSFLM, CM, and MM.

A sensitivity analysis was also conducted for the three assessed meals to better understand which inputs most influence each impact category when varied. Figure 7 presents the results of the sensitivity analyses for the insect meals where each input was

varied by 20%. The results show that electricity is the most sensitive input in most categories for all three insect meals. For BSFLM, chicory roots were the most sensitive input for the MEP impact category and electricity was the most sensitive input for the rest of the categories. For CM, FM was the most sensitive input for the OD impact category, while maize was the most sensitive input for the MEP impact category; heating was the most sensitive for the GWP, SF, AP, and HHC impact categories; and electricity was the most sensitive for the rest of the impact categories. For MM, electricity was the most sensitive input for all categories. For the BRU impact category, the most sensitive inputs were wheat bran for BSFLM, FM for CM, and wheat bran for MM.

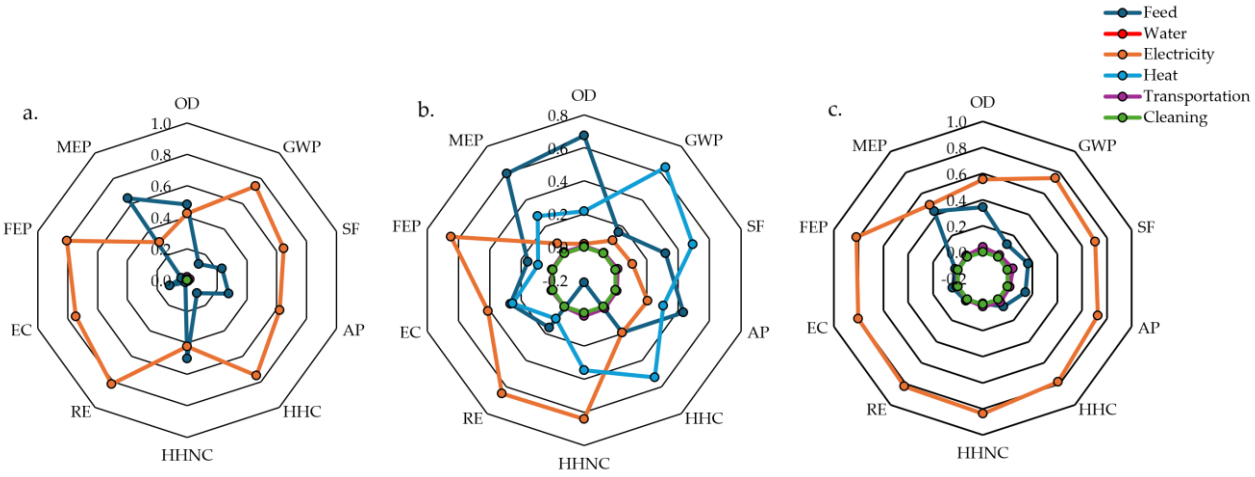


**Figure 7.** Sensitivity analysis results for one tonne of (**a**) BSFLM, (**b**) CM, and (**c**) MM.

## 4. Discussion

The goal of this study is to quantify insect farming in a cold region of the US for the purpose of producing an FM alternative. Insect farming depends heavily on energy to maintain proper temperature, humidity, and ventilation, especially since higher temperatures can increase productivity. Insects are relatively simple to artificially propagate and also utilize significantly fewer biotic resources when compared to conventional FM. Processing insects into a meal is also energy-intensive, as it requires heating and electricity to cook and separate most fatty acids from the protein-rich meal. The impacts of using the current energy mix in the Midwest can be seen in several impact categories, namely GWP and AP, and will be discussed more precisely below.

Based on the results of both assessments, BSFLM seems to be the best choice relative to most environmental impact categories amongst the assessed meals. Although BSFLM does not have the lowest emissions in some categories, changes such as switching out the endive root for a byproduct or waste stream would greatly improve impacts like total AP. Most of BSFLM's lower impacts relative to the other two are due to the lower feed per tonne of meal, the use of agricultural byproducts, and lower electricity input requirements.

### *4.1. GWP Impacts*

GWP is one of the most important impact categories assessed due to rising concerns of anthropogenic GHG emissions and the ever-increasing issue of climate change. GWP investigates the three main GHG emissions commonly produced through industrial processes (carbon dioxide, methane, and nitrous oxide) [42]. Within the BSFLM assessment, electricity was the most impactful, followed by soybean meal (SBM) and potato starch. For CM, the most impactful input for GWP is the heating, followed by rice husk and SBM, respectively. Within the MM assessment, electricity was the main contributor to GWP,

followed by SBM and wheat bran, respectively. Electricity is unsurprisingly a major contributor to GWP for all three assessments given the Midwest's high dependence on coal and NG, which produce all three gases of interest in the impact category [43,44]. SBM, potato starch, and wheat bran are also products which utilize or require machinery for tilling, harvest, and post-harvest processing and synthetic chemicals that are highly dependent on energy consumption, making them more impactful in the GWP category.

### *4.2. BRU Impacts*

Assessing BRU and abiotic resource use in the Anthropocene in general is vitally important, given the rapid depletion of the Earth's resources [45]. BRU also aids in accounting for ecosystem services for resources such as forage fish in LCA, which also allows for a fairer comparison amongst products. In this application, BRU is arguably the most important impact category, given that the purpose of the alternative meals is to replace FM, which is highly dependent on a limited biotic resource (i.e., wild-caught prey fish) [46]. If this impact category were to be omitted, FM seems to be a reasonable protein source for aquaculture in most other environmental impact categories. The main goal of the inclusion of this category for this assessment is to ensure that the insect-based alternatives are not more impactful than their predecessor relative to biotic resources.

For the BSFLM assessment, the most impactful input is the wheat bran given the feed's high reliance on the byproduct. The second most impactful input is the potato starch, which largely comprises amylose and amylopectin, both of which have a base of several carbon atoms. Within the CM assessment, the most impactful input by far was the FM given the products' reliance on higher-trophic-level fish. Grain maize and SBM were the next two feed ingredients with the second and third largest impacts, which is reasonable given both are the main ingredients in this assessment's feed. As one goes up the pyramid of trophic levels, it is expected to require more carbon given the transfer efficiency (~10%) of energy between levels [31]. The CM operation was clearly operating to maximize growth efficiency relative to the feed, given the high reliance on meals and the use of palm oil. For the MM assessment, the most impactful input was the wheat bran, followed by SBM and maize flour, respectively. Both the BSFLM and MM show the benefits of utilizing vegetable-based products and byproducts, though both could also continue to improve in the BRU category by relying more heavily on agricultural waste streams.

### *4.3. AP and MEP Impacts*

AP is another important category to investigate due to rising concerns of ocean waters' chemical composition and the increasing likelihood of acid rain. Relative to AP in the BSFLM assessment, the most impactful inputs are electricity, endive root, and potato starch, which is similar to the MEP category. Within the CM assessment, the largest contributors to AP are potato starch, electricity, and heat. For the MM assessment, the most impactful inputs are electricity, wheat bran, and maize flour. Electricity and NG contribute to this impact category through the combustion of both coal and NG, which produce $NO_x$ and $SO_2$ [44]. Coal combustion is one of the main contributors to $SO_2$ emission in the anthropogenic scene [47]. The feed inputs that also largely contribute to AP are due to the use of fertilizers, which can contain both $NO_x$ and $SO_2$ to help stimulate growth, and there are also no rigorous federal policies and regulations for quantities of fertilizers that can be used, making runoff from these activities a major issue [48].

MEP is generally a necessary impact category to analyze, especially in agricultural applications, given the use of fertilizer in feed production and the growing concern of algae growth. Unsurprisingly, the feed products used in the production of the investigated insect meals were impactful inputs, specifically endive root, potato starch, maize,

and wheat bran. More responsible application of fertilizers either through modified practices of the crop producers or through more strict regulations, would lead to improvements in this category.

### *4.4. Overall Insect Meal LCA Comparisons*

Several studies were chosen for a mass-based comparison as all are either conventional FM (which is still the most viable in terms of availability and cost) or other potential alternatives. Not all impact categories could be compared, due to the differences in LCIA methodologies, which lead to differences in the units utilized (e.g., EC and EP). Table 1 displays this study as well as the referenced literature, along with three impact categories (i.e., GWP, AP, and BRU) that were assessed. As seen in the table, all insect meals have larger impacts for GWP and AP.

**Table 1.** Meal comparisons of GWP, AP, and BRU per tonne of protein produced [49–52].

| Meal Type | Source | Assumed Protein Content (%) | GWP (kg $CO_2$ eq) | AP (kg $SO_2$ eq) | BRU (kg Biotic C) |
|---|---|---|---|---|---|
| BSFLM | This study | 50 | 76,251 | 337.8 | 2582 |
| CM | | 71.9 | 76,895 | 128.8 | 17,198 |
| MM | | 65 | 85,835 | 321.1 | 4611 |
| FM | [36] | 64 | 1641 | 10.61 | 31,063 |
| | [53] | | 2047 | 9.953 | - |
| FM from byproducts | [36] | 61.9 | 4346 | 58.97 | 128,303 |
| | [53] | | 8675 | 91.60 | - |
| Poultry byproduct | [36] | 66 | 6454 | 54.09 | 9029 |
| | [17] | | 3060 | 37.88 | - |
| Soybean | [36] | 46.4 | 717.0 | 6.977 | 923.8 |
| Corn gluten | [36] | 60 | 1600 | 18.50 | 1030 |
| Microalgae (Tetraselmis succia) | [17] | 40 | 38,428 | 97.5 | - |
| Microalgae (Tisochrysis lutea) | | 41 | 66,070 | 195.1 | - |

Apart from the microalgae meals, the majority of these meal types have existed well before insect meals, allowing their systems to be optimized, which helps to show the glaring lack of optimization of insect operations. Most articles did not explore BRU; however, the paper by [36] did for conventional FM, SBM, corn gluten meal, and byproduct meals, and the results are also displayed in Table 1. According to Table 1, the plant-based meals are the least impactful relative to GWP; however, these meals are also lower in protein content, requiring more meal to reach sufficient protein goals for many types of livestock. Based on this comparison, all three insect meals are significantly less impactful in the BRU category than conventional FM and FM byproducts The insect meals require unsurprisingly more biotic resources than the vegetable-based meals, given insects are one trophic level higher than plants, though plant-based meals generally have lower protein contents [54]. Given BRU is one of the major points of interest relative to environmental impacts when exploring alternative meals, the investigated meals are all slightly less than or significantly less than 50% than conventional FM in the BRU category.

### *4.5. Burden Shifting*

Another consideration with insect farming in the US is the concern of burden shifting when using agricultural byproducts. Most, if not all, byproducts are used in animal farming or cropland supplementation, putting more pressure on an already constrained feed stream. One way to mitigate this issue is to further investigate the potential use of animal waste, given insects' ability to efficiently convert waste into biomass. The main issue currently with this change is that there are restrictions on alternative feed streams in the form of governmental regulations in the US, which would need to be altered to allow for commercial use.

### *4.6. Limitations and Recommendations*

Several limitations arose in this study for various reasons. Using non-primary data to develop the inventories limited the ability to fully justify the high electricity use for processing CM and MM compared with BSFLM. More industrial-scale inventories are vital for insect meal to improve as an industry over time. Common practices, energy mixes, feed composition, and infrastructure for insect production and processing may also vary between the US and the countries where the inventories were originally generated. Moisture and the lipid content of the BSFLM could also not be provided, as this information was not provided by the articles sourced for the inventories. The supplemental heating calculations were based on average monthly temperatures for both the original locations and Madison, Wisconsin. Lastly, some of the databases used to build the inventories lacked US-centric data for several inputs, leading to higher uncertainty in the results. The mixture of economic and mass-based allocations of the inputs is also a limitation of this study due to the constraints in available data. This study does not consider factors such as digestibility and amino acid composition of the insect meals studied, though an investigation into these factors is vital in understanding the true viability of insect meal as an alternative to conventional fish meal.

The aquaculture industry is far from being optimized relative to environmental sustainability; however, insect meals could be a way to improve the environmental impacts of the aquafeeds used in operations with further investigation and optimization. There are numerous ways to reduce the environmental impact of insect farming. One example is to utilize waste heat produced during other industrial processes such as papermaking or metal refining; however, this requires another industrial processing plant to be close to the insect operation, which is highly unlikely in most cases. Another, more obvious option is to utilize more renewable energy sources. Currently, the Midwest energy mix depends heavily on coal and natural gas, making both inputs highly impactful across many categories, as discussed earlier. One of the main concerns with a meal alternative such as insect meal is the high temperature and humidity requirements for proper growth and cycle time. Utilization of renewable energy would greatly reduce environmental impacts; however, the costs for said energy source could make this option untenable for some. Improving efficiency within the operation itself is another option for reducing environmental impact, which includes minimizing the total space that needs heating; exploring high densities within the colonies, given there are no stringent standards on this type of farming (the farmer would need to ensure that a non-cannibalistic species is selected); and exploring various kinds of feeds to either significantly decrease cycle time or investigate feed amounts per cycle (all three operations output large amounts of uneaten food). Relative to the LCA itself, using primary data would reduce uncertainty in the assessments. Another recommendation for future environmental assessments like this is to explore scenarios to better understand the meal's full potential, including the previously discussed recommendations. Conducting and comparing techno-economic analyses is also vital to understanding the viability of insect meals, given the financial constraints of many

livestock producers. A final recommendation for future-related environmental assessments is to utilize economic allocation of the meal and oil to better understand how the market value of the products influences environmental impacts.

## 5. Conclusions

Finding a more sustainable protein source for animal farming, specifically aquaculture, is imperative as global demand for aquatic species increases and wild-caught fish harvests stagnate. Insect meal as an alternative to conventional FM and other alternatives is currently not viable from an environmental impact standpoint across most impact categories; however, it performs better in terms of BRU in this theoretical operation. Optimization of rearing densities, environmental conditions, overall system design, and energy sources will drastically improve the environmental impact of insect meals in the US; however, these changes still may not be enough to justify replacing conventional fish meal with insect meal. As environmental viability improves, the insect farming industry can move towards larger-scale operations, thus allowing for economies of scale and other positive factors to take place, which will lead to improvements relative to economic sustainability [55].

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments13120654/s1, Table S1: BSFLM inventory and sourcing, Table S2: CM inventory and sourcing, Table S3: MM inventory and sourcing, Table S4: BRU calculations and sources for BSFLM, Table S5: Chicken feed BRU calculations, Table S6: BRU calculations and sources for CM, Table S7: BRU calculations and sources for MM, Table S8: BRU calculations and source for palm oil, Figure S1: Theoretical insect operation dimensions with an assumed height of 10 feet with 10-inch-thick concrete walls, Equation S1: Theoretical operation heating, Table S9: Location, climate, and average seasonal temperatures of the studied theoretical operation and related published LCAs for supplemental heating calculations, Table S10: Example of supplemental heating calculation (BSFLM), Table S11: LCA results for one tonne meal, Table S12: Mass-based allocation of insect meal and oil LCA results for one tonne meal, Table S13: LCA results for one tonne of insect meal protein. [56–62]

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