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Comparative Assessment of Insect Processing Technologies for Sustainable Insect Protein Production

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Abstract: Considering the projected increase in demand for protein sources, finding alternative sources with lower environmental impacts has become of great importance. Insect mass production has emerged as a potential solution, particularly in Western countries. Previous studies indicate that insect farming together with insect processing stages are responsible for most of the environmental impacts associated with the final product. This study compares the environmental impacts linked to alternative processing technologies for insect protein production to traditional ones using a Life Cycle Assessment (LCA) following the Environmental Footprint methodology. The most relevant impact categories were identified as land use, energy use, freshwater ecotoxicity, water use and climate change. Among the processing treatments, FOP (freezing–oven drying–hot pressing) showed the best environmental performance in terms of all selected impact categories except water use, while the BOS (blanching–oven drying–SFE with CO_2) group had the highest environmental impacts in all categories. The results from this study indicate that the environmental impacts of insect protein production can be reduced by using alternative processing technologies. These findings underscore the importance of carefully selecting processing technologies in order to align with global sustainability ambitions in the food industry. This study contributes to the development of ecologically responsible methods that can be adopted across protein production industries.

Keywords: *Hermetia illucens*; insect protein; LCA; environmental impact

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1. Introduction

Insects are recognized as a highly promising protein source for the future, particularly due to their high nutritional value, efficiency and potential to alleviate food insecurity [1]. Additionally, insect production offers a more sustainable alternative with a smaller ecological footprint compared to traditional livestock farming practices involving vertebrates like cattle and swine, which are related to surface and groundwater contamination by nutrients, toxins and pathogens as well as the significant release of substantial amounts of ammonia, among other environmental problems [2,3]. In fact, insect farming is awakening interest (mostly due to sustainability issues) in recent years in markets that have not been traditional consumers of these kinds of products, like European and Northern American countries. Hence, the demand for insect-based products is on the rise, leading to increased production and trade volumes [4]. According to the International Platform of Insects for Food and Feed, insect food business operators produced about 500 tonnes of insect-based products in 2019 and are expected to produce about 260,000 tonnes by 2023.

Some of the most common insects that are being farmed for food and feed purposes include crickets like *Acheta domesticus*, mealworms like *Tenebrio molitor* and flies like *Musca domestica* and *Hermetia Illucens* (black soldier fly, BSF). In particular, the BSF has several major advantages over other insect species. For instance, BSF larvae can break down different types of organic material like fruits, vegetables and animal manure [5–7]. Their use for the latter organic material is pretty interesting since, as mentioned by Erickson et al. [8], BSF larvae inactivate pathogen bacteria like *Escherichia coli* O157:H7 and *Salmonella* species, which are present in animal manure.

Currently, the production of insects at an industrial scale is carried out by a reduced number of companies, with their main target group being pets and livestock feed [2,9]. Hence, the information about insect processing methods is scarce and usually only available at a laboratory scale [10]. Satisfying the quality standards related to insect protein digestibility for animal feed holds utmost importance. However, an even more crucial factor is to ensure food safety [11]. The first step in obtaining edible insect products is to harvest and separate them from the residues, followed by their killing and washing [12]. In the case of larvae/worms, they are usually separated by sieving and sacrificed by blanching to reduce the microbial population, with the food spoilage and poisoning degradative enzymes being inactivated as well [13].

The aim of drying processing technologies is to reduce the total water content. This limits the degradative reactions, which at the same time increases the shelf-life of foods [14]. Some examples of the drying techniques used are roasting and sun-drying (traditional processes) or more recent ones like freeze-drying and drying assisted by microwaves. In particular, to obtain edible insect meal and powder, some of the most used techniques are drying by the sun, oven or freezing [15,16].

One of the key processes in obtaining protein-enriched ingredients from edible insects is the defatting step due to the high fat content of insects [17]. Moreover, insects that have undergone defatting exhibit elevated nutritional value and enhanced functionality compared to raw insect protein [18]. One of the mostly widely used extraction processes of lipids in the food industry is performed using hexane due to its high oil recovery ability [19]. However, the use of hexane is not currently considered a good option as it presents some constraints in health, safety, environmental and economic terms; thus, other options were recently investigated for its substitution [20]. Some examples of alternative methods are aqueous extraction, three-phase partitioning and supercritical fluid extraction (SFE) with CO_2 and mechanical pressing [21]. In the case of mechanical pressing (dry processing), this step is performed using a screw press at an industrial scale. Moreover, additional heating improves the defatting process by mechanical pressing [22]. With regard to alternative defatting techniques, defatting by means of SFE with CO_2 showed promising results (95% oil recovery from *Tenebrio molitor*). However, this treatment method shows high operating costs at an industrial scale [23]. Therefore, SFE using CO_2 could become in a real alternative technique when it is optimized and, thus, the costs are reduced.

It is worth mentioning that the current studies on insect larvae processing are primarily focused on individual evaluations of the three previously described processes—sacrifice, drying and defatting—without consideration for their collective application towards the final product of insect meal [24–28]. While several studies examined the different methods of sacrifice, drying or defatting, there remains a gap in research that explores the interconnectedness of these three technological processes as successive operations within a single, cohesive production process. Exploring the collective application of sacrifice, drying and defatting processes as successive operations in the production process of insect proteins is important for several reasons: product quality and safety, efficiency and cost effectiveness, nutritional value optimization, sustainability, etc. [1].

In short, there are diverse challenges to insect processing to be addressed, such as (i) the development of efficient technologies, (ii) the promotion of environmentally friendly practices and (iii) the establishment of cost competitiveness. Although several authors evaluated the environmental impact of insect production, most of these studies' final product focus was whole larvae/worms with few processing steps included [26,28–30]. Considering that farming and processing of insect proteins contribute the most to the overall environmental impact and may not always be favorable when compared to traditional protein feeds [31], obtaining a true environmental assessment from insect production systems is of vital importance for the further expansion and up-scaling of the insect industry. Thus, the present study aims to analyze the environmental impacts associated with insect protein production including all processing steps (sacrifice, drying and defatting) and covering different available technologies (blanching, freezing, oven drying, lyophilization, hot pressing and SFE with CO_2). These technologies are combined in order to study the interconnectedness of these three technological processes. In addition, the resulting processing treatments are compared to determine which processing treatment is the most environmentally friendly.

2. Materials and Methods

2.1. Processing Treatments

This study investigated three insect processing steps: sacrifice, drying and defatting. Two technologies were examined for each processing step. Regarding sacrifice technologies, blanching (B) and freezing (F) were analyzed, while oven drying (O) and lyophilization (L) were chosen as drying technologies. Moreover, hot pressing (H) and SFE with CO_2 (S) were selected for the defatting processing step. Given that blanching, oven drying and pressing are commonly used on an industrial scale [13,15,21], BOP was set as the reference baseline scenario.

Processing treatments were created by substituting one processing step with an alternative technology, with reference to the baseline case. Thus, the processing treatments were FOP, BLP and BOS (Figure 1). It should be noted that an extra freezing step is required for lyophilization, and an additional grinding step is needed prior to SFE with CO_2.

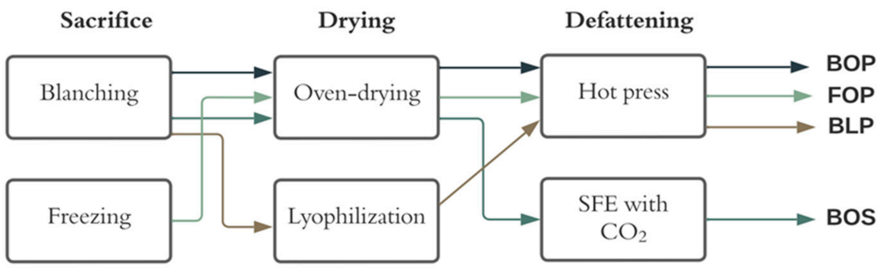

Figure 1. Insect processing treatments investigated in this study.

2.2. Life Cycle Assessment

A Life Cycle Assessment (LCA) is a multi-criteria tool used to analyze and evaluate environmental impacts linked to products and/or services throughout their complete life cycle considering several impacts related to human health, the environment and resources [32]. The LCA procedure is specified by ISO standards 14040 and 14044 [33,34]. An LCA study is composed of four steps: (1) goal and scope definition, (2) Life Cycle Inventory (LCI), (3) Life Cycle Impact Assessment (LCIA) and (4) interpretation of results. In the goal and scope definition step, the aim of the study, system boundaries and functional unit (FU) are defined. In the LCI step, the data to be used are gathered and referred to the established FU. In the LCIA step, data from the inventory are related to their impact on the environment. Finally, in the interpretation step, the results are discussed and recommendations are provided.

2.2.1. Goal and Scope

Goal

Considering that the insect production sector is moving from experimental or small-scale operations to large-scale industrial production, the goal of this study is to quantify the environmental impacts linked to the production and further traditional processing (blanching, oven drying and hot pressing) of the BSF in order to make a comparison with alternative processing steps (freezing, lyophilization and SFE) and determine which is the most environmentally friendly.

Functional Unit

The FU is the reference unit of the whole system. That is to say, all the input and output flows must be referred to this unit for their quantification. The use of an FU is required to ensure the system representativity and comparability among systems. In this way, the FU selected for the present study was 1 kg of insect protein since this source of protein is considered as an alternative protein source for animal feed.

System Boundaries

The type of LCA considered here is "cradle-to-gate". Thus, the stages included in this analysis are (1) raw material cultivation and processing, (2) substrate preparation, (3) egg production and colony maintenance, (4) larvae and compost production and (5) larval processing. The process includes the colony maintenance as well. A general scheme of the system boundaries considered in this study is presented in Figure 2.

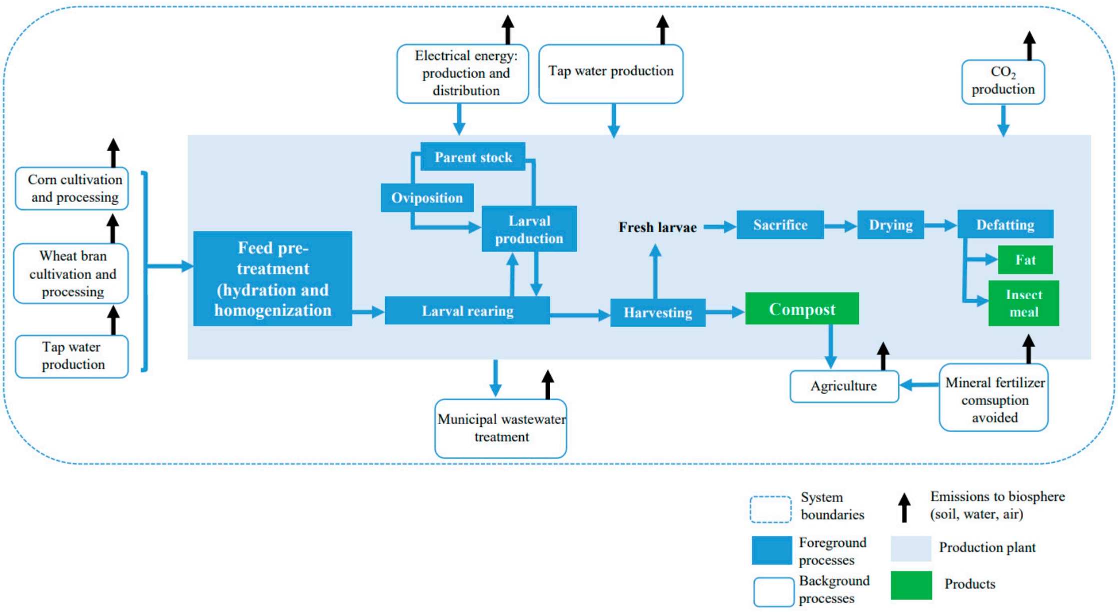

Figure 2. System boundaries for BSF larvae production and processing considered for this study.

In the production of the BSF protein, three different products are obtained: proteins, fats and compost, a stabilized substrate excreted by larvae. Insect feed is composed of a mixture of corn and wheat bran. The cultivation, collection, transport and processing of corn and wheat bran is considered. Moreover, during feed pre-treatment, water is added to the mixture, and thus, water production is also included.

After the fattening period, fresh larvae and substrate (compost) are separated. Afterwards, larvae are washed, sacrificed, dried and defatted. The first product (fats) can be used as insect oil (coproduct), whereas the solid paste is the main product (insect meal). The protein content of the insect meal ranges between 65 and 72%. At this point, it is interesting to mention that not all the larvae are transformed into insect meal: 5% of the larvae is left to reach the adult stage to keep colony maintenance. During this stage, electricity and water are consumed. Electrical energy and tap water production impacts are considered in this study. Moreover, in the case of the BOS treatment, CO_2 production by the Haber–Bosch process is considered. In these stages, wastewater is produced and for this reason, municipal wastewater treatment is also considered in the system boundaries of this study.

Allocation: As observed in Figure 2, there are two by-products of the BSF protein production process: compost and fats. With regard to compost, system expansion was adopted and thus, allocation was avoided. The environmental impacts for the BSF protein production processes were distributed among the BSF protein and fat. The considered allocation factors were calculated based on the mass product (solid) obtained, being 20%

and 80% (BOP and FOP), 24% and 76% (BOS) and 12% and 88% (BLP) for fat and protein, respectively. Allocations were applied throughout the whole process. Another spread allocation factor is based on the economic value of the product. However, this was discarded because of the high fluctuation in prices once the insect industry scales up.

2.2.2. Life Cycle Inventory

The Life Cycle Inventory (LCI) shows data related to the studied system and the calculations performed in order to quantify both inputs (i.e., energy and raw materials) and outputs (i.e., emissions to air, soil and water). These data are linked to the reference unit, named as FU. The mentioned data are compiled in Tables 1–4.

Table 1. Life Cycle Inventory using traditional processing technologies (BOP) to obtain 1 kg of insect protein from BSF.

Stage	Inputs			Outputs		
Larval bioconversion	Feedstock	13.00	kg	Fresh larvae	8.42	kg
	Electricity	36.38	MJ	Wastewater to WWTP	3.60	kg
	Tap water	46.83	kg	Compost	12.43	kg
	Sawdust	0.03	kg			
Sacrifice (blanching)	Fresh larvae	8.42	kg	Dead larvae	4.42	kg
	Tap water	1.68	kg	Wastewater to WWTP	1.68	kg
	Electricity	0.89	MJ			
Drying (oven)	Dead larvae	4.42	kg	Dried larvae	1.41	kg
	Electricity	22.31	MJ			
Defatting (hot press)	Dried larvae	1.41	kg	Protein	1	kg
	Electricity	1.27	MJ	Fat	0.25	kg
Compost production	CAN27	−0.63	kg			
	$TS46P_2O_5$	−0.46	kg			
	KCl—60%K_2O	−0.75	kg			

Table 2. Life Cycle Inventory using freezing as sacrifice method (FOP) to obtain 1 kg of insect protein from BSF.

Stage	Inputs			Outputs		
Larval bioconversion	Feedstock	7.00	kg	Fresh larvae	4.53	kg
	Electricity	19.59	MJ	Wastewater to WWTP	3.26	kg
	Tap water	25.22	kg	Compost	6.70	kg
	Sawdust	0.02	kg			
Sacrifice (freezing)	Fresh larvae	4.53	kg	Dead larvae	4.42	kg
	Electricity	1.27	MJ			
Drying (oven)	Dead larvae	4.42	kg	Dried larvae	1.41	kg
	Electricity	22.31	MJ			
Defatting (hot press)	Dried larvae	1.41	kg	Protein	1	kg
	Electricity	1.27	MJ	Fat	0.25	kg
Compost production	CAN27	−0.34	kg			
	$TS46P_2O_5$	−0.25	kg			
	KCl—60%K_2O	−0.41	kg			

Table 3. Life Cycle Inventory using lyophilization as drying method (BLP) to obtain 1 kg of insect protein from BSF.

Stage	Inputs			Outputs		
Larval bioconversion	Feedstock	11.78	kg	Fresh larvae	7.63	kg
	Electricity	32.96	MJ	Wastewater to WWTP	3.26	kg
	Tap water	42.43	kg	Compost	11.26	kg
	Sawdust	0.03	kg			
Sacrifice (blanching)	Fresh larvae	7.63	kg	Dead larvae	4.01	kg
	Tap water	1.53	kg	Wastewater to WWTP	1.53	kg
	Electricity	0.81	MJ			
Drying (freezing + lyophilization)	Dead larvae	4.02	kg	Dried larvae	1.32	kg
	Electricity	23.63	MJ			
Defatting (hot press)	Dried larvae	1.32	kg	Protein	1	kg
	Electricity	1.56	MJ	Fat	0.14	kg
Compost production	CAN27	−0.57	kg			
	$TS46P_2O_5$	−0.42	kg			
	KCl—60%K_2O	−0.68	kg			

Table 4. Life Cycle Inventory using SFE as defatting method (BOS) to obtain 1 kg of insect protein from BSF.

Stage	Inputs			Outputs		
Larval bioconversion	Feedstock	13.00	kg	Fresh larvae	8.42	kg
	Electricity	36.38	MJ	Wastewater to WWTP	3.60	kg
	Tap water	46.83	kg	Compost	12.43	kg
	Sawdust	0.03	kg			
Sacrifice (blanching)	Fresh larvae	8.42	kg	Dead larvae	4.42	kg
	Tap water	1.68	kg	Wastewater to WWTP	1.68	kg
	Electricity	0.89	MJ			
Drying (oven)	Dead larvae	4.42	kg	Dried larvae	1.41	kg
	Electricity	22.31	MJ			
Defatting (grinding + SFE)	Dried larvae	1.41	kg	Protein	1	kg
	Electricity	446.49	MJ	Fat	0.32	kg
	CO_2	88.73	kg			
Compost production	CAN27	−0.63	kg			
	$TS46P_2O_5$	−0.46	kg			
	KCl—60%K_2O	−0.75	kg			

The foreground processes in this study relied on inventory data that were derived from a combination of primary and secondary sources. When primary data were insufficient or not assimilable to an industrial-scale system, secondary data from bibliographic sources were used instead. Each inventory flow was estimated using primary data, except for the electrical consumption of the lyophilization step in the BLP treatment, where secondary data were utilized [35].

Several background processes were included in the scope of this study. However, the inputs and outputs of these processes were not added to the inventory tables due to their complex nature. The background processes considered are the production of electricity, production of tap water and treatment of wastewater generated in the urban wastewater treatment plant. In addition, the CO_2 manufacturing process was included as a background process in the BOS processing treatment. The inventories of all these processes were obtained from the Sphera LCA software database.

2.2.3. Life Cycle Impact Assessment

The results obtained in the present study were based on a professional Sphera LCA software v10.5 6.2.9 (Sphera Solutions GmbH, Chicago, IL, USA). The mentioned LCA software included the Environmental Footprint (EF) v3.0 methodology, which was used to calculate the midpoint of potential environmental impacts [36]. Sphera LCA software serves as a versatile and wide-ranging tool for conducting comprehensive Life Cycle Assessments, while the EF methodology provides standardized guidelines for consistent and comparable environmental assessments. The EF was chosen because it is a methodology fostered by the European Commission to assess the products/services within the European markets under the same parameters.

A total of 16 impact categories are analyzed by the EF methodology. Nevertheless, a short group of five categories were considered for the present study: (i) land use; (ii) energy use; (iii) freshwater ecotoxicity; (iv) climate change and (v) water use. These impact categories were selected according to their relevance among all impact categories after data normalization and weighting. In order to facilitate comprehension, a short description of each impact category selected for this study is displayed in Table 5.

Table 5. Description of the different impact categories considered in this study.

Impact Category	Unit	Description
Land use	Pt	Quantification of alterations in soil quality (biotic production, erosion resistance and mechanical filtration).
Energy use	MJ	Indicator of the exhaustion of inherent fossil fuel reserves.
Freshwater ecotoxicity	CTUe	Influence of noxious compounds released into the environment on freshwater organisms.
Climate change	kg CO_2 eq.	Measure of potential global warming resulting from the release of greenhouse gases into the atmosphere.
Water use	m^3 world eq.	Metric representing the proportional water consumption, determined by localized factors of water scarcity.

2.2.4. Interpretation of Results

To determine the relative contribution of each impact category, a contribution analysis was performed to identify the most relevant impact categories linked to each processing treatment. Additionally, another contribution analysis was carried out to identify the key processes associated with each processing treatment. Finally, a comparative assessment was performed in order to identify the most environmentally friendly processing treatment in line with the goal and scope previously defined.

3. Results

The results obtained from the production and processing of 1 kg of the BSF protein are shown in the present section. In the first part, a contribution analysis of the impact categories is presented, followed by a process contribution analysis. Finally, a comparison among the processing treatments studied is shown.

3.1. Contribution Analysis of Impact Categories

Based on the normalized and weighted results, the most relevant impact category was identified as land use, with a cumulative contribution of 99.08, 92.82, 99.04 and 98.87% of all environmental impacts to BOP, BOS, BLP and FOP, respectively. Moreover, energy use, freshwater ecotoxicity, water use and climate change impact categories were selected. The five selected impact categories contributed to 100% of the total environmental impacts in the BOP, BLP and FOP processing treatments, while they contributed to 99.40% in the BOS processing treatment (Table 6).

Table 6. Relative contribution of each impact category to the overall environmental impact.

Impact Category	BOP	BOS	BLP	FOP
Climate change	0.02	0.09	0.02	0.02
Freshwater ecotoxicity	0.08	0.32	0.08	0.09
Land use	99.08	92.82	99.04	98.87
Water use	0.02	0.06	0.06	0.03
Energy use	0.81	6.11	0.84	0.99

3.2. Processes Contribution Analysis

Environmental impacts were caused by different processes involved in the BSF protein production and processing. Figures 3 and 4 depict the relative contributions of the different processes involved in all the studied impact categories.

Corn and wheat bran cultivation, recollection and processing were found to be the processes with the most significant contribution, accounting for more than 85% of the environmental burdens in the land use impact category for all processing treatments (Figure 3A).

Regarding the energy use impact category, electricity production and corn grain cultivation processes were the most relevant for the BOP, BLP and FOP processing treatments. In particular, electricity accounted for 65.86% and corn grain cultivation for 17.81% (averaged across the three treatments). For the BOS processing treatment, electricity production accounted for 64.02%, while carbon dioxide production contributed 31.38% of the energy use impact category (Figure 3B).

In terms of the impact on freshwater ecotoxicity, the key factors for all processing treatments were determined to be electricity production and corn grain cultivation, recollection and processing for the BOP, BLP and FOP processing treatments. On average, these factors accounted for 50.71% and 34.43%, respectively. However, for the BOS group, electricity production was the most relevant contributor, accounting for 81.32% of the impact (Figure 4A).

Regarding water use, the most significant processes varied among the different processing treatments. For all treatments, corn grain cultivation, recollection and processing, followed by electricity production, were identified as the primary factors. However, their contributions differed significantly. In the case of the BOP, BLP and FOP processing treatments, corn cultivation accounted for 56.62%, while electricity production contributed 33.17% to water use. In contrast, for the BOS processing treatment, electricity production was the dominant factor, accounting for 78.18%, followed by corn cultivation, which contributed 18.22% (Figure 4B).

In terms of the climate change impact category, electricity production and corn cultivation were found to be the most significant processes across all BOP, BLP and FOP groups, contributing over 80% of the environmental burdens. In the case of the BOS experimental group, electricity production (71.34%) and CO_2 production (20.32%) were identified as the primary contributors to the climate change impact category (Figure 4C).

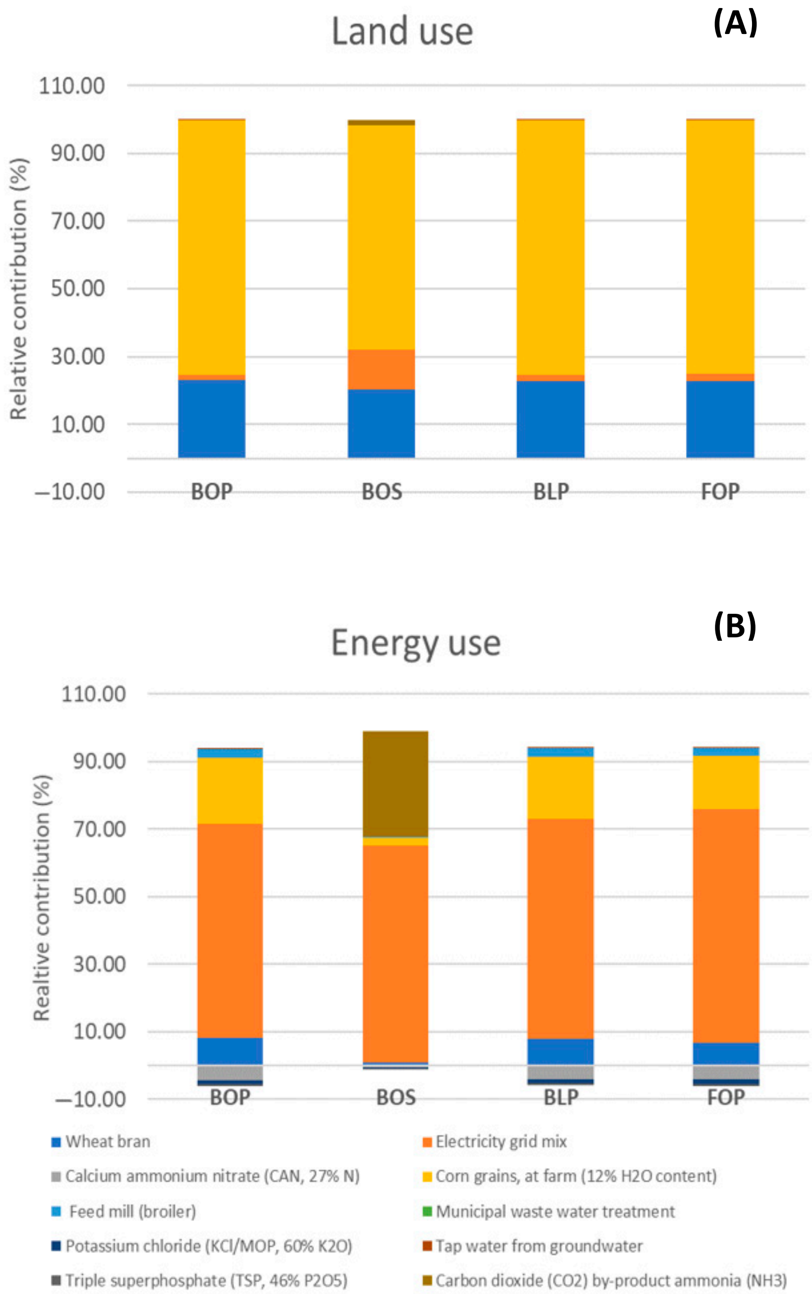

Figure 3. Contribution of the most relevant processes to land use (**A**) and energy use (**B**) impact categories to each of the processing treatments studied.

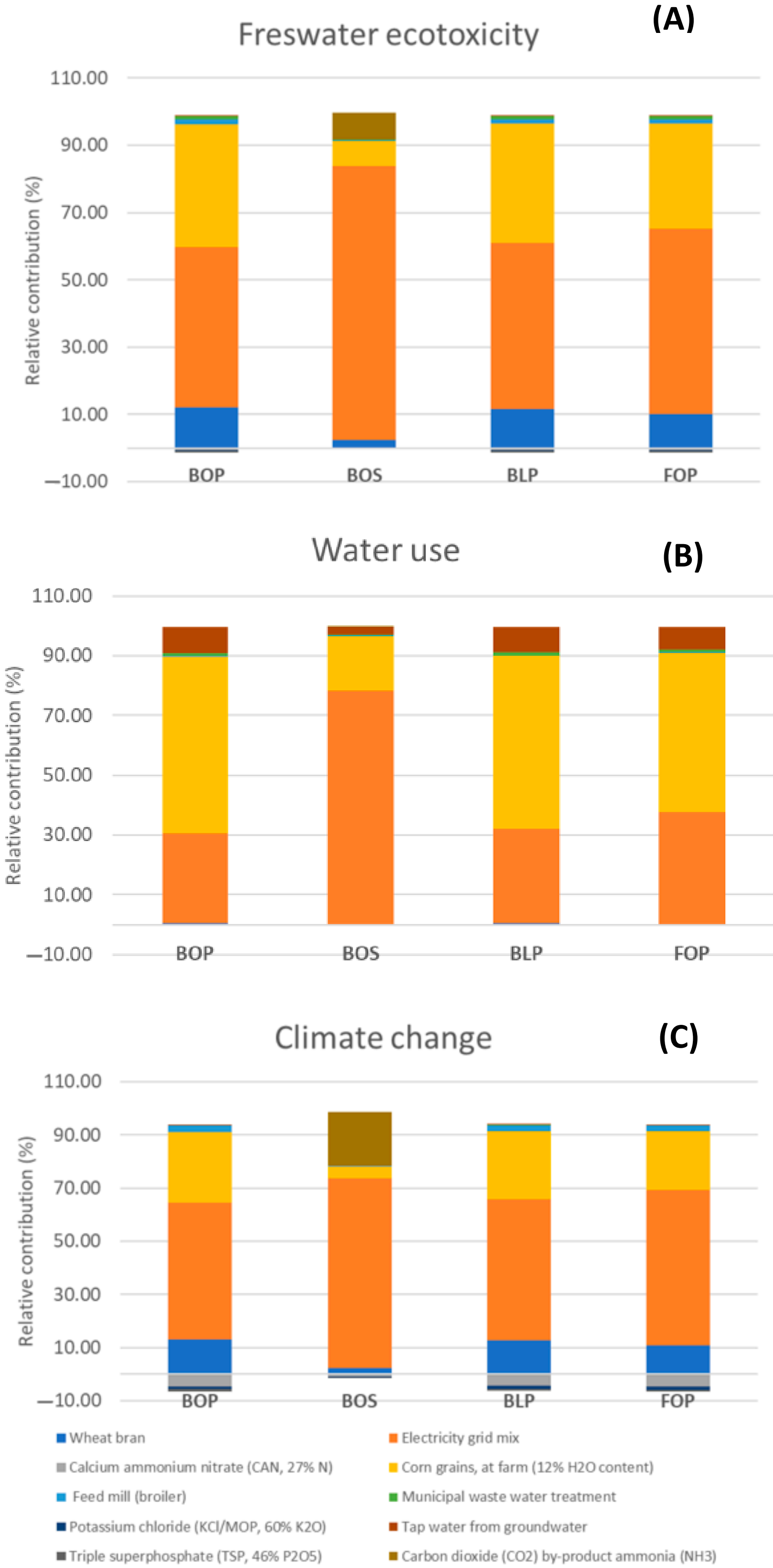

Figure 4. Contribution of the most relevant processes to freshwater ecotoxicity (**A**), water use (**B**) and climate change (**C**) impact categories to each of the processing treatments studied.

3.3. Comparison of Processing Treatments

In the following section, the production and processing of 1 kg of the BSF protein using standard and alternative insect processing technologies are analyzed and compared. The results obtained in the comparison of 1 kg of the BSF protein obtained through the combination of the different technologies are shown in Table 7.

Table 7. Comparison of Life Cycle Impact Assessment of 1 kg of BSF protein obtained using different processing technologies.

Impact Category	Unit	BOP	BOS	BLP	FOP
Land use	Pt	1177.81	1270.42	1174.95	638.90
Energy use	MJ	115.27	4105.45	120.36	35.21
Freshwater ecotoxicity	CTUe	55.78	262.01	57.24	35.31
Water use	m^3 world eq.	18.29	56.93	18.5	10.88
Climate change	kg CO_2 eq.	7.73	49.04	7.99	4.97

The environmental impacts of the BOS treatment were consistently higher across all selected impact categories. Specifically, land use, energy use, freshwater ecotoxicity, water use and climate change were observed to be 1.07, 8.72, 4.70, 3.11 and 6.34 times higher, respectively, compared to the BOP control group, which served as the benchmark insect processing technology.

In contrast, both the BLP and BOP processing treatments demonstrated comparable environmental performance across all selected impact categories. However, the FOP processing treatment exhibited superior environmental performance in all selected impact categories. Specifically, land use, energy use, freshwater ecotoxicity, water use and climate change were found to be 1.84, 1.50, 1.58, 1.68 and 1.55 times lower, respectively, compared to the BOP processing treatment. In general, the outcomes of this investigation indicated that the FOP treatment displayed lower environmental impacts across all selected impact categories, whereas the BOS treatment consistently demonstrated higher impacts compared to the other treatments under examination.

4. Discussion

This study investigates and compares different processing technologies for insect protein production in terms of their environmental impacts. It particular, it aims to contribute to the development of sustainable and efficient insect value chains by analyzing the potential environmental burdens associated with each processing method. The BOS treatment consistently had higher environmental impacts mostly due to energy-intensive CO_2-based extraction, whereas the FOP processing was the eco-friendliest, with lower impacts across all categories, indicating its potential for improving insect protein production's environmental impact through optimized processing.

The selection of impact categories in LCA studies for insect production may vary de-pending on the specific context and objectives of the study. Nevertheless, common impact categories examined in insect production include land use, climate change, energy use and water use, as supported by previous studies [24,25,37–39]. Similarly, the most relevant impact categories identified in this study included land use, energy use, freshwater ecotoxicity, water use and climate change. These categories were chosen based on their relevance to the environmental impacts associated with insect protein production and processing. In particular, the analysis performed in this study revealed that land use had the highest contribution to the overall environmental impact across all processing treatments studied.

The analysis of process contributions provided insights into the specific stages that significantly influenced the environmental impacts of the processing treatments. Corn and wheat bran cultivation, collection and processing emerged as the most relevant processes across several impact categories, particularly land use. In this particular case, corn and wheat bran cultivation environmental impacts were attributed to land occupation. Considering that corn and wheat were destined for a BSF feed substrate, alternative feeds must be considered and further studied, as was reported in previous studies [5,6,26,30]. These findings emphasize the need for sustainable sourcing practices and efficient resource management in the insect industry, such as optimizing feed production. Moreover, electricity production was consistently identified as a significant process contributing to multiple impact categories, in particular climate change, freshwater ecotoxicity and energy use. This highlights the importance of transitioning towards renewable energy sources to reduce the environmental burden associated with insect production.

The comparison of processing treatments revealed important differences in their environmental performance. The BOS treatment consistently demonstrated higher environmental impacts across all selected categories compared to the BOP control group. These elevated impacts can be attributed primarily to the substantial energy demand associated with SFE extraction using CO_2, which emerged as the key driver behind these findings. In this sense, the SFE extraction process can have a high energy demand due to several contributing factors, such as high pressure and temperature requirements, compression of supercritical fluid, heat transfer, cooling, etc. On the other hand, both the BLP and BOP treatments showed comparable environmental performance, indicating that the use of alternative drying methods (lyophilization) did not significantly affect the overall environmental impacts when compared to the standard processing technologies. The FOP processing treatment stood out as the most environmentally friendly option among the evaluated processing treatments. It exhibited lower environmental impacts in all selected categories compared to the rest of processing treatment. These results suggest that replacing the sacrifice step with freezing instead of blanching has the potential to enhance the environmental performance of insect processing. The freezing–oven drying–hot pressing combination proved to be a more sustainable approach, suggesting that optimizing the processing sequence can lead to improved environmental performance in insect protein production.

In conclusion, this study shed light on the environmental impacts of different processing treatments for insect protein production. By analyzing the contributions of various impact categories and processes, valuable insights were gained regarding the sustainability of insect protein production and the importance of selecting appropriate processing technologies, offering valuable insights for stakeholders, decision makers and researchers. Throughout this manuscript, it is evident that different combinations of processes significantly influenced both environmental impacts and the efficiency of fat and protein extraction, as illustrated in the inventory data. From an environmental standpoint, the results highlighted the most environmentally favorable operational processes for insect protein production while pinpointing critical areas for improvement, primarily related to the raw materials utilized for insect feed. These findings provide guidance for decision makers, emphasizing the importance of considering the use of secondary raw materials for insect feed. Consequently, future research should prioritize demonstrating the safety of such materials for the insect sector. This approach has the potential to mitigate the primary environmental impact category identified in this study: land use.

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