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Review

Greenhouse Gas Emissions and Life Cycle Assessment on the Black Soldier Fly (*Hermetia illucens* L.)

Kofi Armah Boakye-Yiadom, Alessio Ilari and Daniele Duca *

Department of Agricultural, Food and Environmental Sciences, Università Politecnica delle Marche, Via Brecce Bianche 10, 60131 Ancona, Italy

* Correspondence: d.duca@staff.univpm.it; Tel.: +39-071-2204631

Abstract: The black soldier fly (BSF) is recognised as a valuable insect for mitigating feed and organic waste management challenges. Thus, concerted efforts are being directed toward the promotion of the BSF. Despite the numerous advantages of BSF larvae, there are several critical environmental aspects, particularly its global warming potential, that need to be considered before large-scale adoption due to the complexity of the insect's value chain. The direct assessment of greenhouse gas (GHG) and ammonia emissions from BSF larvae biotreatment is crucial for conducting a life cycle assessment (LCA) to evaluate the insect products' environmental performance. This article reviews the emissions of GHG from BSF larvae bioconversion activities based on different gas sensing techniques while highlighting the factors that influence these emissions. Generally, low gas emissions were reported. However, the influence of various factors influencing emissions remains unclear, especially for nitrous oxide. We also analysed LCA studies on BSFL products while emphasising the uncertainties and variabilities among the studies. The wide variation of impact scores reported in the studies suggests that standardised guidelines should be developed to streamline methodical approaches for impact assessments pertaining to system boundaries, functional units, allocation, and system expansion assumptions. We identified several aspects for future improvements to harmonise studies in order to enhance the comparative assessment of the BSFL products.

Keywords: environmental sustainability; environmental impact; climate change; edible insect; gas sensing; waste biotreatment; bioconversion; insect products

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1. Introduction

Food production systems are associated with several processes and activities threatening the sector's environmental sustainability. The agri-food sector is responsible for an estimated 23% of the total greenhouse gas emitted annually [1]. Enteric fermentation in livestock, the increased use of agrochemicals, biomass burning, and food waste are significant factors accounting for greenhouse gas emissions [2]. As the world's population grows, food production patterns must change significantly to meet present and future needs. It is estimated that food and feed production will increase by 70% by 2050 to meet human and animal dietary needs [3,4]. Thus, finding innovative and sustainable solutions to this challenge has become a universal goal.

Insects are promising as a food source and a resource for environmental remediation, thus attracting attention to their breeding and bioconversion activities. The black soldier fly (*Hermetia illucens* L.) is one such insect, recognised as a critical component in establishing a circular economy within agri-food production systems. It can feed on a wide array of organic substances and consume over twice its body weight in feed material [5,6]. The larvae can transform and recover nutrients from different organic compounds and reduce organic waste biomass by 50–60% [7]. Regarding the larvae's proximate composition, crude protein and fat vary between 30–52% [6] and 15–50% [6–8] of dry weight, respectively. Carbohydrates, primarily chitin, range between 8–24% of dry matter [9]. The larvae contain

many essential and non-essential amino acids and substantial quantities of polyunsaturated fatty acids [10–17]. The feed conversion ratio of the larvae is estimated to be between 1.5 and 12.5, often influenced by substrate quality [6,13,14,18–22]. The larvae can also reach 27 mm in length and 6 mm in width by the prepupae stage [23], with their body weights also ranging between 113 mg and 225 mg [24–26]. This ability to rapidly convert even low-quality carbon materials into high-quality larval biomass accounts for its increased application in waste management.

The BSFL is recognised as a viable and promising protein source both nutritionally and environmentally. Increasing meat production poses a significant threat to the environment as it places immense pressure on scarce resources such as water, energy, and land [27]. Livestock production, especially cattle, is responsible for considerable annual greenhouse gas emissions, between 15–18% (CO_2 equivalent), directly impacting climate change [28–30]. Animal feed production is also recognised as a significant contributor to the environmental impacts associated with meat production. Due to the high nutritional properties of BSF larvae, they can serve as an affordable feed substitute for more competitive ingredients such as soybeans and fish meals in poultry [10,31–41], fish [42–62], swine [63–67], and cattle [68] production. *H. illucens* is included in the European Commission's and the European Food Safety Authority's developed list of insects suitable for animal nutrition [69]. Thus, substituting BSFL proteins with conventional animal feed sources can improve the sustainability of meat production systems.

A wide range of organic waste management applications exists for *H. illucens*, with promising environmental benefits. Reducing food waste is essential due to its negative ecological, social, and economic impacts [70,71]. Food waste has a global carbon footprint of about 8% of all global anthropogenic greenhouse gas emissions, making it a significant contributor to climate change [72]. Thus, the European Green Deal stresses eliminating waste and reducing greenhouse gas emissions in food systems to reach carbon neutrality [73]. Agri-food residue can be a valuable resource given the beneficial products that can often be derived after processing. Additionally, biowaste represents a significant part of municipal solid waste (about 70%), especially in low- and middle-income countries. The BSFL can valorise residual biomass to ensure the continued use of resources and reduce waste in a circular economy context. BSFL can significantly reduce the volume of waste to be incinerated or disposed of, possibly up to 85% [74]. BSFL waste treatment aligns with the EU Landfill Directive regarding reducing the amount of municipal waste disposed of in landfills to 10% or less of the total volume of waste generated by 2035 [75]. This can reduce the health risks associated with uncontrolled waste burning, common in low-income countries, and hazardous emissions from landfills since there is less need for landfills and incinerators.

Despite the numerous benefits of *H. illucens*, the insect value chain is associated with complex and intertwined environmental and socio-economic impacts, such as other food and energy supply chains. Industrial rearing, processing, and valorising *H. illucens* to obtain proteins, lipids, chitin derivatives, bioactive peptides, organic fertiliser, biogas, and other micro- and macro-nutrients are complex and intensive tasks [76]. Several unit operations, including substrate transportation, breeding, extraction and separation mechanisms, fractionation techniques, and biorefining schemes, optimise *H. illucens* biomass production and quality [76]. Therefore, to promote the utilisation of *H. illucens*, it is imperative to accurately assess the environmental profile of its various processes and activities.

The life cycle assessment (LCA) is a decision-making tool that provides a comprehensive overview for evaluating a product's environmental performance during its entire life cycle. LCA offers a strong ecological tool in the movement toward sustainability as it helps identify ecological hotspots for improvement. Recently, LCA has gained wide acceptance and use in evaluating agri-food activities and processes [77,78]. It can support research and development, product and process development, labelling, marketing, and policy making. LCA communication can positively influence the purchase of eco-friendly products amid the growing consumer interest in environmental sustainability [79,80]. The environmental

performance of products or processes that perform similar functions can be compared using the LCA to select the most environmentally sustainable option.

The harmonisation of LCA methodology is essential for a fair and more accurate comparison of environmental sustainability between different products. Data quality and key assumptions can significantly affect the accuracy and reliability of LCA result results, leading to wrong conclusions [81]. Sometimes, the unavailability of the correct inventory data can hinder the inclusion of key inputs or emissions in inventory modelling. Conducting an LCA for BSFL products requires data on direct greenhouse gas (GHG) emissions from the bioconversion phase. Most LCA studies on BSFL struggle to consider these emissions as part of their inventory modelling, mainly due to the unavailability of reliable background data. Some studies did not include it under the assumption that it was negligible [70]. Others also included emission data for other insects [82,83], which is not ideal. Few studies have been conducted to directly measure GHG emissions from BSFL biotreatment to address this limitation. However, wide variations exist among the results obtained due to differences in substrate, experimental conditions, and sampling and analytical methods [84–91]. Thus, relying on secondary data from these sources may lead to the inclusion of wrong emission estimates, increasing data uncertainty and reducing the reliability of the results, as the conditions under which the gases were produced may not be similar.

Given this topic's growing traction and importance globally, it is essential to streamline all environmental impact assessment information available on the black soldier fly. This review aims to summarise the current knowledge and provide a comprehensive analysis of the ecological sustainability of black soldier fly production, specifically, direct greenhouse gas emissions, potential environmental impacts, and life cycle assessments. We discuss several issues that can guide LCA practitioners in assessing the ecological impacts of the black soldier fly.

The outline for this review is as follows: Section 2 presents an overview of the method used in conducting the study. Section 3 discusses the greenhouse gases associated with BSFL production and the factors influencing the emissions of these gases. Sections 4 and 5 describe the commonly used methods and analytical techniques to quantify GHG emissions from BSFL biotreatment and their limitations. Sections 6 and 7 explore LCA studies carried out on BSF production, variations in methodological approaches, and some key environmental impacts assessed. Section 8 highlights critical outstanding issues from the review and suggests a pragmatic approach to addressing these issues.

2. Methods

This review summarises multiple studies dealing with detecting and measuring GHGs, ammonia emitted during BSFL rearing on a range of feeding materials, and life cycle assessment studies on the insect. We conducted a comprehensive literature search using the Science Direct, ISI Web of Knowledge, and Google Scholar databases to identify relevant studies evaluating greenhouse gas emissions from BSF production and the environmental impact of BSF products and bioconversion activities from a life cycle perspective. We used keywords such as black soldier fly AND greenhouse gas; *Hermetia illucens* AND greenhouse gas emissions; black soldier fly AND ammonia; black soldier fly AND life cycle assessment; *H. illucens* AND environmental impact; *H. illucens* AND global warming; black soldier fly AND food waste; and black soldier fly AND bioconversion in an iterative process.

We considered mainly peer-reviewed or original research papers written in English. However, due to the limited life cycle assessment studies on BSF, we included one conference paper and a published master thesis. To this end, 21 articles were selected and categorised according to their relevance to *H. illucen*'s greenhouse gas emissions and life cycle assessments. However, two articles fell under both categories. The papers selected for the review were not restricted to any geographical location. For gas emission studies, we included only those that assessed emissions of at least one greenhouse gas with a detailed description of the gas sampling and measurement procedure. Moreover, we

selected studies that provided sufficient information on the substrate used for feeding and some characteristics of the larvae before and after biotreatment. Regarding the LCA section, we considered only studies from 2000 to reflect the actual state of the art and recent developments (the first ISO 14040–14043 series began between 1997–2000). We included only studies based on the methods described in the ISO 14040 and 14044 standards, where methods and single processes are described in detail. Additionally, we selected only studies reporting results for at least one impact category and studies that provided a quantitative description of the LCA of the BSF production chain, not just basic details.

3. Gases Associated with Insect Production

BSF breeding and bioconversion activities are recognised as emitting some greenhouse gases and ammonia, which could influence their product's overall environmental performance. Several factors influence the type and concentration of greenhouse gases emitted during BSFL rearing. These parameters, such as substrate quality, experimental design parameters, ambient conditions, sampling procedure, and gas detection and measurement methods, account for GHG emission variations between studies (Table 1). The substrate quality plays a crucial role in terms of the growth rate and quality of the BSFL biomass and can also impact total GHG emissions. Dietary parameters, volume, moisture content, sensory characteristics, chemical properties, rheology, porosity, and pre-treatment contribute to digestibility, mobility, and microorganism survival and proliferation, affecting GHG emissions. Experimental parameters, including larvae age before the experiment; the larvae density; feed rate; feeding strategies, such as continuous, intermittent, and bulk; and the housing chamber can also influence GHG emissions [92]. Extrinsic parameters such as ambient conditions, including temperature, humidity, ventilation rate, and light intensity can also affect the metabolic activities of BSFL and the microorganisms present [93,94].

Table 1. A review on quantifying greenhouse emissions per kg of dry matter BSF larvae biomass (mean ± standard deviation) during rearing and bioconversion.

Substrate	Larvae Age (Days)	Larvae Density (Larvae/cm^2)	Feeding Rate (mg dm/Larva/Day)	CO_2 (kg/kg dm BSFL)	CH_4 (mg/kg dm BSFL)	N_2O (mg/kg dm BSFL)	NH_3 (g/kg dm BSFL)	References
Chicken feed	7–10	–	12.61	2.2 ± 1.30	Negligible	–	–	[5]
Food waste	5	2	30.00	1.75 ± 0.17	49 ± 29	21 ± 13	–	[88] [d]
Kitchen waste	5	4	26.00	–	5.5	118	–	[90] [d]
Pig manure + corn cob	3	0.34	38.38	2.73	455.71	1.52	8.35	[87] *
Food waste + rice straw	3	0.64	23.30	1.39 ± 0.34	14 ± 6	7 ± 1	–	[86] [a,d,*]
Pig manure + corn cob	3	1.2	15.65	1.59 ± 0.13	5411.58 ± 3655	13.79 ± 3.46	7.32 ± 5.02	[84] [b,*]
Meat and bone meal + rice bran	3	1.13	26.67	3.33 ± 0.37	348.35 ± 390.08	6.52 ± 3.85	0.11 ± 0.02	[85] *
Yeast concentrates from wheat + starch-rich byproduct	7	6.6	16.57	2.75 ± 0.31	19 ± 10 [c]	53 ± 27	–	[92] [d]
Pig manure	7	4.7 ± 0.5	22 ± 2	344 ± 43	10,066 ± 2652	6 ± 14	–	[95] [d]
Food waste	4	17.95	67.85	1.17	64.31	0.33	2.90	[91]
Orange peels	–	6.25	7.75	5.83–34.04	22.71–208.43	3.02–24.16	0.00–18.06	[89]
Broccoli + cauliflower trimmings	–	6.25	3.07	3.77–22.71	561–805.86	46.35–1904	4.33–125.27	[89]
Food waste	–	6.25	15.00	1.36–2.70	8.27–12.77	8.27–12.77	8.27–56.56	[89]

Calculations and assumptions for gas emissions: From Ermolaev et al. (2019) [88], we used the values of treatment "L". From Chen et al. (2019) [87], we used 75% moisture content. From Pang et al. (2020 [a]) [84], we used the values of treatments pH 5, pH 7, and pH 9. From Pang et al. (2020) [86], we used the average of all five C/N ratio treatments. From Zhang et al. (2021 [b]) [85], we used values for all five treatments. From Guo et al. (2021) [91] we used the primary results for CH_4 and N_2O obtained in the study and not the secondary data in the LCI table. [c] We used mean and standard deviation values without including the outlier reported in their study. [d] Adapted from Parodi et al. 2021 [92]. * We assumed the dry matter content of the larvae to be 35%.

3.1. Carbon Dioxide

Carbon dioxide (CO_2) is the most important GHG and is the primary gas produced from the BSFL rearing process starting from organic matter. CO_2 is primarily released during respiration and the metabolic activities of the BSFL and microorganisms, as well as the biodegradation of the organic substrate [84,86,87]. CO_2 can be derived from either biogenic or non-biogenic sources. A large part of biogenic CO_2 emissions originates from the aerobic decomposition of organic matter and anaerobic processes or the oxidation of CH_4 by aerobic methanotrophic bacteria [96]. The amount of biogenic CO_2 released during the breeding process can indirectly indicate the biodegradation rate of the organic feedstock and the metabolic activities of the BSFL and microorganisms present [5,88]. In

general, the global warming potential (GWP) of biogenic CO_2 emissions is not included in the environmental assessment of the biological degradation process since it is regarded as neutral carbon. Nonetheless, measuring CO_2 emissions can be useful in understanding carbon cycling and carbon mass balance in BSFL biotreatment [5,86,97]. Compared to conventional waste management, such as composting, the BSFL degradation of organic waste releases lower carbon emissions. BSFL can readily recycle significant quantities of carbon into high-value insect proteins and oils, a better alternative to converting them into carbon dioxide and methane during composting [5].

Some studies have measured the CO_2 emitted during BSFL rearing and bioconversion activities on different substrates (Table 1). On average, CO_2 emissions were between 1–4 kg CO_2 eq./kg of dry matter BSFL biomass, except for fruit and vegetable waste (orange peels, broccoli, and cauliflower trimmings) [89]. In most studies, CO_2 showed a trend of low emissions in the first few days, a gradual increase and peak emission rates during mid-treatment, and a gradual decline in the latter days due to the stability of the substrate and a reduction in the metabolic activities of the BSFL and microorganisms. Some parameters that can affect the rate of CO_2 emissions during the breeding of BSFL are summarized in Table 2. However, experimental parameters such as larvae density, feeding strategies, and ambient conditions such as temperature on CO_2 emissions during breeding have not been thoroughly investigated. Non-biogenic CO_2 emissions from BSFL rearing, on the other hand, may derive from energy and fuel use in the breeding plant. The assessment of these emissions is important in evaluating the environmental impacts of operating a BSFL plant [70]. However, the emissions depend on the type and quantity of energy and fuel being used, the technologies and equipment employed, and additional operational activities [91,96].

Table 2. The effect of some substrate parameters on the cumulative greenhouse gas emissions and ammonia during BSFL biotreatment.

Substrate Parameter	Carbon Dioxide (CO_2)	Methane (CH_4)	Nitrous Oxide (N_2O)	Ammonia (NH_3)	Reference
C/N ratio	Generally, substrates with a higher C/N ratio are rapidly degraded, increasing the respiration rate and consequent high CO_2 loss during larvae growth. Thus, higher cumulative CO_2 emissions were observed among treatments with higher initial C/N ratios, with 15 (108 g CO_2 eq./kg substrate) being the lowest and 25 (152 g CO_2 eq./kg substrate) being the highest.	C/N ratio inversely correlates with CH_4 emissions due to reduced easily degradable C sources.	Generally, very low emissions were detected. However, a low C/N ratio resulted in higher NH_3 emissions. BSFL activity could create a conducive aerobic environment that leads to the inhibition of denitrification and thus limits the N_2O production.	A low C/N ratio resulted in higher NH_3 emissions, suggesting that a high C/N ratio of substrate improves microbial assimilation and thus reduces NH_3 emissions. On the other hand, a higher proportion of corncob as part of the BSFL feedstock improves the water-holding capacity, therefore partly reducing NH_3 volatilization.	Pang et al. [84]
Moisture content	Total emissions correlated positively with increasing substrate moisture content and the overall BSFL biomass yield.	High substrate moisture content positively correlated with higher CH_4 emissions due to low oxygen concentration and the formation of anaerobic zones, favouring the growth of methanogenic bacteria.	No clear relationship between moisture content and N_2O emissions.	A negative correlation between moisture content and NH_3 emissions was observed, mainly due to the solubility of NH_3 in water, and the ability of high moisture content substrates to absorb large amounts of NH_3.	Chen et al. [87]
pH	Emissions were lowest for extreme pH conditions (pH 3.0 and 11.0) and highest at optimum pH conditions of 5.0 and 7.0.	Decreasing the pH of the feeding material also corresponds to a decrease in CH_4 production since acidic conditions inhibit methanogen activity.	Relatively higher emissions were associated with lower pH treatments, although no statistically significant differences were obtained.	Neutral to high pH (7.0–11.0) resulted in higher cumulative NH_3 emissions.	Pang et al. [86]
Batch feeding time	Increasing the batch feeding times increased CO_2 emissions and BSFL biomass.	The periodic addition of substrate led to the formation of an anoxic environment under the substrate surface, increasing CH_4 emission.	No clear relationship between batch feeding times and N_2O emissions, as no statistically significant difference was observed among the various treatments.	Increasing batch feeding times increased the cumulative NH_3.	Zhang et al. [85]

3.2. Methane

Methanogens produce methane in organic-rich environments primarily through deoxidising CO_2/H_2 and acetic acid under anaerobic conditions [84,86,87]. Methane (CH_4) is generated in small quantities, but it has a global warming potential that is 28 to 36 times greater than that of carbon dioxide (100-year timescale), making it a significant contributor to climate change [98]. The emission of CH_4 is heavily reliant on anaerobic conditions during organic degradation [99]. Generally, BSFL rearing releases low emissions of CH_4 because BSFL breeding occurs under semi-aerobic conditions, leading to significantly lower fractions of CH_4 emissions than the conventional anaerobic decomposition of organic matter in landfills [5]. Although the gut microbiome of the BSFL has not been found to generate CH_4 [100], the rearing process of BSFL has been reported to emit varying levels of CH_4, as

shown in Table 1. The general emissions trend for CH_4 shows that emissions are highest within the first 3–4 days of biodegradation. The BSFL takes about two weeks to reduce substrate particle size. Therefore, the high emission during the early phase is attributed to the anaerobic conditions in certain substrate zones. The BSFL extends its activities over the entire substrate through bioconversion processes and peristaltic movement, consequently improving air circulation and reducing CH_4 production [88,90]. Factors influencing the concentration of CH_4 emitted during BSFL biotreatment, including the substrate's quality in terms of nutritional quality, moisture content, and pH, are summarized in Table 2.

3.3. Nitrous Oxide

Nitrous oxide (N_2O) is a potent GHG with a global warming potential 298 times greater than CO_2 that destroys the ozone layer [98,101]. N_2O synthesis through biodegradative processes is an intricate system since it can be formed via different microbial pathways at various pockets in the substrate. Thus, it is necessary to identify the microorganisms responsible for specific processes during substrate biodegradation. Nitrous oxide is produced as an intermediate or byproduct of nitrification and denitrification processes [102]. In nitrification, microorganisms convert ammonium salts to nitrates under aerobic conditions, and in denitrification, they convert NO_3^- to N_2 [103]. Aerobic nitrification requires the initial conversion of ammonia into nitrite by ammonia-oxidising bacteria, such as *Nitrosomonas* and *Nitrososporas*. The nitrite is then converted to nitrate by nitrite-oxidising bacteria such as *Nitrobacter* [96,102]. On the other hand, denitrification is regarded as the primary source of N_2O [96]. The denitrification process is also an anoxic process that involves denitrifiers, which are heterotrophic microorganisms that reduce NO_3^- to N_2 by using NO_3^- as their electron acceptor [96]. Nitrifiers and denitrifiers are regulated by available C sources, oxygen conditions, pH, and the temperature in the substrate [96,97,104].

BSFL production is associated with very low N_2O emissions (Table 1), and in many cases, N_2O concentration does not differ significantly from the ambient air. Just as CH_4, N_2O is emitted under anaerobic conditions during composting, aeration within the substrate caused by BSFL feeding and movement inhibits denitrification by reducing the number of denitrifiers, resulting in low N_2O emissions [101,103,105,106]. The BSFL gut microbiome has not been reported to produce N_2O directly [100], while the effect of saprophages on N_2O emissions remains unclear during decomposition [107]. Although a symbiotic relationship may exist between the bacteria community in the gut and the substrate in producing N_2O, no studies have been conducted to confirm this postulate [84].

3.4. Ammonia

Ammonia (NH_3) is typically not regarded as a GHG. However, due to its propensity to negatively impact the environment by causing acid rain, its emissions are studied during the biodegradation of organic matter [96]. Ammonia can also be a precursor for the formation of secondary pollutants such as N_2O [108]. However, few studies have measured NH_3 emissions during BSFL breeding and bioconversion operations (Table 1). Generally, the emission trend of NH_3 during BSFL rearing shows high concentrations in the initial phases and reduces rapidly after a few days [84,86,87] due to fast organic degradation and the conversion of NH_4^+–N to NH_3 [87,109,110].

3.5. Other Greenhouse Gases

There are several potentially harmful greenhouse gases that are emitted by the breakdown of organic materials, including carbon monoxide (CO) and nitrogen oxides (NO_X). While carbon monoxide and nitrogen oxides make minor contributions to direct global warming potential, both substances lead to indirect global warming by increasing CH_4 lifetimes and elevating tropospheric O_3 concentrations [96]. CO is emitted during the aerobic decomposition of organic material through physical processes and biological activities. NO_X (NO and NO_2) is also released as either a byproduct or intermediate of nitrification

and denitrification processes [96]. There are no studies on the gases produced by BSFL breeding and bioconversion activities.

Secondary pollutants, such as peroxyacetyl nitrate (PAN), which are not emitted directly from BSFL rearing, may be synthesised through several chemical reactions. The primary precursors for these reactions include the gaseous oxides of nitrogen, such as NO and NO_2, which are released from organic matter biodegradation [111]. Recently, secondary pollutants have gained attention because they can damage vegetation and affect human health. However, no studies have evaluated whether NO_X emissions from BSFL breeding and bioconversion activities contribute to secondary pollutant formation.

4. Direct Greenhouse Gas Assessment Methods

The goal of reducing greenhouse gas emissions from the agri-food sector cannot be achieved without correctly detecting and quantifying these gases. Several methodologies have been applied to develop techniques and devices to accurately measure CO_2, CH_4, and N_2O fluxes or emissions into the atmosphere to characterise GHG sources and sinks. The sampling devices and techniques for measuring field and laboratory greenhouse gas emissions include chamber systems, tunnel methods, eddy covariance, relaxed eddy accumulation, sampling in containers, adsorbent sampling, and integrated horizontal flux [112,113]. However, each process has different pros, cons, and susceptibilities to measurement errors.

4.1. Chamber System

The chamber system coupled with sampling in containers is the most used method for sampling greenhouse gases during BSFL rearing (Table 3). BSFL are bred under intensive systems, often in wooden or plastic boxes, making it easy to house them in chambers. Thus, this review will only focus on this sampling device. Chamber systems can be classified as closed static, closed dynamic, automated, or open chambers.

The closed static chamber method is the most common system used to sample GHG emissions from BSFL production. It is a simple device that allows for the concentration of target gases in the chamber headspace over the enclosed area [114]. The enclosed space could be either a box or glass jar for laboratory analysis or the entire production room of a facility. The concentrated gas inside the headspace changes over time and can be converted into a flux rate [115]. A syringe can easily extract the headspace gas for gas chromatography analysis. Fans can also be installed in the chamber to improve the mixing and circulation of air [88,89]. They also do not require very sensitive, accurate, or rapid analytical techniques because the extracted gas contains concentrated target compounds [116]. The device is also affordable, easy to install, and allows for multisite observations [112,113].

Closed dynamic systems share many similarities with closed static systems, though some modifications have been implemented. The main difference is that the dynamic system is optimised to measure gas continuously by connecting the gas analysers to the sampling points outside the chamber. The accumulated gas in the chamber is pumped through the gas analyser or sensor for detection and quantification. Compact non-dispersive infrared (NDIR) sensors and laser-based trace gas analysers can measure CO_2, CH_4, and N_2O. The closed dynamic system addresses the challenge of wide variations in target gas concentrations, resulting in higher concentration changes within the chamber headspace contrary to what is observed in the closed static chamber. This saves the time and cost of designing specific chambers and sampling protocols for measuring the different gases. Guo et al. [91] measured greenhouse gas emissions from a BSFL treatment plant designed as a closed dynamic chamber fitted with several fans and outlets for gas sampling.

The automated closed chamber system is simply an advanced closed static or dynamic chamber with a moveable lid that allows for gaseous exchange via a pneumatic system without the assistance of an operator [117]. In the case of the automated closed dynamic chamber, the system is more accurate due to its better sampling frequency and integrated fluxes. It is considered a real-time gas measurement method since it captures possible

fluctuations in emissions over the study period [113,118]. Unlike a closed chamber, an open chamber continuously pumps ambient air through the chamber until a steady-state is achieved. A gas analyser measures the concentration difference at the inlet and outlet of the chamber to determine the gas flux [117]. Due to their simplicity, open chambers are easier to use and have a smaller chamber effect than closed chambers because no manual or automatic door-opening is required. The main drawbacks of open chambers are the continuous air stream (different from natural conditions) and the pressure difference between the atmosphere and the chamber headspace [119]. Parodi et al. [92] designed an open-circuit climate respiration chamber with a recirculating fan to measure real-time greenhouse gas emissions during BSFL bioconversion activities.

Table 3. Sampling methods and techniques used for measuring greenhouse gas and ammonia emissions during BSFL biotreatment.

Ref.	Sampling Method	Sampling Procedure and Frequency	Study Period	CO_2	CH_4	N_2O	NH_3
[5]	Closed static chamber/syringe	Three times every morning: one immediately (t = 0), at 3 min (t = 3), and at 6 min (t = 6) after sealing the jar.	7 days	NDIR	GC–FID	–	–
[88]	Closed static chamber + fan/syringe	Three days: 2, 7, and 11 (5-day intervals). Samples were taken at intervals of 0, 15, 30, and 60 min.	14 days	GC–TCD	GC–FID	GC–ECD	EC gas detector tube system
[90]	Closed static chamber + fan/syringe	Daily in triplicates	13 days	–	GC–FID	GC–ECD	–
[87]	Closed static chamber/syringe	Every morning	8 days	GC–FID	GC–FID	GC–ECD	Trapped in an H_2SO_4 solution and then measured using titration with a NaOH solution
[86]	Closed static chamber/syringe	Daily at 0 and 20 min after the container closure	10 days	GC–FID	GC–FID	GC–ECD	Tapped in an H_2SO_4 solution and then measured using titration with a NaOH solution
[84]	Closed static chamber/syringe	Daily at 0 and 300 s	12 days	GC–FID	GC–FID	GC–ECD	Trapped in an H_2SO_4 solution and then measured using titration with a NaOH solution
[85]	Closed static chamber/syringe	Every morning	10 days	GC–FID	GC–FID	GC–ECD	Trapped in an H_2SO_4 solution and then measured using titration with a NaOH solution
[92,95]	Open chamber + fan/syringe (N_2O only)	Daily. Every 9 min from the ingoing (CO_2 and CH_4) and outgoing airstream (CO_2, CH_4, and NH_3). N_2O samples were taken every 24 h (at noon).	8 days	NDIR	NDIR	GC–ECD	EC gas analyser
[120]	Closed static chamber	Daily at 11:00 h at intervals of 0, 10, 20, 40, and 60 min.	6 days	–	GC–FID	–	–
[91]	Closed dynamic chamber + fan/ sampling bag and tube	Sampling was performed over a three-day period in 4 h intervals (4:00, 8:00, 12:00, 16:00, 20:00, 24:00).	10 days	–	GC– ns	GC–ns	EC gas detector
[89]	Closed static chamber + fan/syringe	Samples were taken four times, three between 1 to 7 d and the last between 7–25 d depending on the BSFL composting duration (directly upon sealing the box, after 20 min, and after 1 h).	17–35 days	EC gas detector tube system	GC–FID	GC–ECD	EC gas detector tube system

NDIR—non-dispersive infrared analyser, GC—gas chromatography, FID—flame ionisation detector, ECD—electron capture detector, TCD—thermal conductivity detector, EC—electrochemical, Ns—detector not specified.

4.2. Sampling in Containers

Gas samples from the commonly used chamber systems are often collected in sampling containers and sent to the laboratory for the chromatographic analysis of target gas molecules. Regarding GHG emissions from BSFL rearing, several sample containers can be involved in gas extraction and transportation for gas chromatography analysis. Syringes are mostly used to extract gas samples, which are later transferred into glass vials. The glass vials are sometimes prefilled with argon [90], N-evacuated [88,89], or pre-evacuated [84,86,87]. However, gas-tight syringes can be fitted with Luer locks for

direct storage and transport [5]. A specialised sampler system consisting of a sampling bag, sampling tube, and a vacuum pump was used to collect air samples from a BSFL treatment plant (closed dynamic chamber system) [91]. The major challenge of using syringes is that only small volumes of air are taken from the closed chambers, usually between 30 and 100 mL [5,84,86–90,92].

In contrast, sampling bags are often used in open chambers to allow them to be filled over a more extended period while capturing an average concentration [113]. The air is sampled by placing the sampling bag in a container connected to a pump. This option is quite popular as it is inexpensive and easy to use, although not in the case of BSFL GHG emission studies. Molecular diffusion and film permeation, which can lead to sample loss, are the sampling bag's main drawbacks [121].

Canisters can also collect air samples either with sub-atmospheric pressure sampling or with pressurised sampling using a sampling pump. Pressurised sampling can extract larger sample volumes. Stainless-steel canisters have features such as inertness, ruggedness, reusability, and durability, but they require special equipment for cleaning and preparing samples, which comes at an additional cost [121,122].

5. Analytical Techniques for GHG Measurement

Modern analytical techniques used in quantifying GHG are based on various physical or chemical principles. These analytical sensing techniques can be classified under three main groups: chromatographic, optical, and electrochemical [113,123], some of which have been used to measure GHG emissions from BSFL breeding. Table 3 summarises the different types of analytical techniques that have been applied in BSFL studies.

5.1. Chromatography

Gas chromatography (GC) is the most common sensing technique used in measuring GHG from chamber systems. GC can be used for qualitative and quantitative analysis and is a highly efficient technique used in testing environmental samples to monitor pollution. Several sensitive detectors are available and can be coupled to GC to detect the target GHG compounds. The thermal conductivity detector (TCD), the flame ionisation detector (FID), the electron capture detector (ECD), and the mass spectrometer (MS) are the major detectors currently in use for trace gas sensing. The selection of a detector is primarily based on its sensitivity to the target molecule, stability and reproducibility, response time, sample destructibility, and working temperature [113,124]. As mentioned earlier, before GC analysis, samples are collected into containers using syringes and glass vials.

FID has been widely applied to measure CH_4 directly, although it can be used for CO_2 and CO quantification if they have been catalytically converted to CH_4 prior to the analysis [123]. FID is highly sensitive, especially for organic compounds, while inert to the presence of moisture or air in carrier gas [124]. In FID analysis, injected samples are directed toward an air–hydrogen flame at a high temperature, causing the decomposition of the sample to release ions and electrons. However, the sample cannot be recovered since it is a destructive method. The target gas species are quantified using FID by measuring the difference in electrical conductivity since gases act as insulators at normal temperatures and pressures but become conductive when exposed to electrons by a high impedance picometer [125]. Several studies report using FID to measure CH_4 and CO_2 emissions during BSFL rearing (Table 3).

TCD determines target molecules based on the difference in thermal conductivity of pure carrier gas and gaseous solute molecules. It is a simple detector that produces a linear response [124,125]. TCD is mainly used to measure CO_2 from BSFL biotreatment, although it has been coupled with an FID to measure CH_4 [88].

ECD is chiefly used to detect and quantify N_2O emissions during BSFL breeding due to its high sensitivity to electronegative atoms, such as nitrogen, up to ppb or ppt levels [123,125]. The ECD technique involves injecting large gas headspaces into packed columns. Samples need to be pre-treated to eliminate water vapour and CO_2 to avoid

inaccuracy. Choosing a suitable carrier gas is also important since contaminants such as O_2 influence the ECD response to N_2O [123]. Argon or purified nitrogen are the main carrier gases often used, as reported in some BSFL GHG emission studies [87–89]. A GC may also be connected to multiple detectors (TCD, ECD, and FID), allowing for the measurement of several GHGs at once [113].

MS is a powerful detector that has high accuracy and sensitivity. It measures the mass-to-charge ratio of ions produced from samples based on ionisation and fragmentation. High bombarding energy from the detector causes the sample to lose electrons in order to become ionised. The further bombardment of the ionised sample leads to fragments, creating total ion chromatography to determine several target GHG species in a single run. Some limitations of MS include high cost, low throughput, and difficulty in introducing reactive gases intact [123,126,127].

5.2. Optical Gas Sensing

The luminescence/optical gas sensor detects changes due to the absorption of chemical species at specific frequencies of the electromagnetic spectrum caused by the interaction of an analyte with a receptor. Unlike GC, it can provide real-time data on the quantitative detection of gases [128]. Optical techniques include non-dispersive infrared spectroscopy (NDIR), Fourier-transform infrared spectroscopy (FTIR), tunable diode laser spectroscopy, cavity-enhanced techniques, quantum cascade lasers (QCLs), and photoacoustic spectroscopy (PAS).

Direct gas flow monitoring can be achieved with infrared (IR) and near-infrared (NIR) spectroscopy by measuring the specific vibrational transitions of molecular bonds [129]. NDIR gas sensors and the FTIR spectrometer are the most common gas analysers that function best in the IR and NIR spectral regions. NDIR measures gas concentration by analysing the difference between the infrared light emitted by a lamp source and the light that reaches the detector after passing through the gas particles and an optical filter. It has high accuracy, a short response time, good performance, and is relatively cost-effective. NDIR is most suitable for detecting CO_2 with low calibration requirements. Regarding BSFL biotreatment, NDIR is the only optical gas sensor used to determine emitted GHGs, specifically, CO_2 and CH_4 [5,88,92].

Fourier-transform infrared spectroscopy (FTIR) is a non-intrusive technique that detects molecules based on their unique vibrations, dependent on their functional groups, after exposure to infrared light. FTIR gas analysers work in IR and NIR spectral regions and can detect multiple components in real-time in a short time. Modern FTIR spectrometers can quantify a wide range of analytes with precision down to parts-per-billion concentrations and are commercially available as portable devices for continuous field analysis. However, infrared sensors are limited to measuring gases with nonlinear molecules and can be affected by atmospheric gases, including water vapour and ozone. Although FTIR spectroscopy has been used to measure greenhouse gas concentrations, such as CO_2 and N_2O from agricultural soils [130] and animal production, it has not yet been applied to BSFL biotreatments.

Laser-based gas analysers are instruments that use a laser source to measure the type and amount of the element in the gaseous phase by detecting the absorption of a specific light wavelength by the target molecules. Laser diodes operate at wavelengths from the visible to the mid-infrared range, depending on the target gas [128,131]. In addition to being suitable for the multicomponent analysis of gases and other chemical species for various processes, laser spectroscopy is an ideal method for trace gas analysis because a spectrally narrow laser source focuses on a narrow region of the analyte's absorption spectrum [132]. Tunable diode laser absorption spectroscopy (TDLAS), quantum cascade laser, and cavity ring-down spectroscopy (CRDS) are popular laser-based gas analysers in many industries. Although laser-based spectroscopy is a promising technique for gas sensing, it is typically sensitive to reflected (feedback) light and temperature variations and is less reliable and affordable [128,133].

TDLAS is a promising technique for detecting specific gases because the laser's wavelength of operation can be adjusted in a controlled manner depending on the application [134]. They are highly sensitive with a rapid response time. They can measure several gases without interference from other trace gases [134,135].

In CRDS, a short laser pulse is injected into an optical cavity with two highly reflective mirrors. The light is reflected back and forth as it passes through, leading to the exponential decay of the light. By measuring the decay time (ring-down time), CRDS analyses the light intensity variations resulting from cavity loss due to absorption by target molecules [136,137]. CRDS is a direct quantitative gas sensing technique that is more sensitive than conventional absorption spectroscopy and GC techniques and relatively resistant to power fluctuations. However, a drawback of CRDS is the need to fit the recorded signal to exponential decay, as multiple exponential decay terms can be challenging to fit [113,131].

The quantum cascade laser (QCL) is a high-intensity and broadly tunable mid- to far-infrared laser instrument that can work at room temperature. Mid-IR absorption bands are typically stronger than NIR absorption bands, which leads to higher resolution, faster measurement, and more precise results for trace gas sensing [128,138,139]. Regarding GHG emissions from BSFL biotreatments, laser-based gas analysers have not yet been used to detect and quantify the target gases.

Photoacoustic spectroscopy (PAS) is another innovative technique commonly used in gas quantification. Unlike laser spectroscopy, a PAS measurement is made when light is absorbed by gases and transformed into heat, which relies on light intensity in the presence or absence of a target species. The analyte and surrounding matrix expand when the temperature rises, and if the light is chopped or modulated, the expansion generates pressure waves detectable by a microphone [140–142]. A significant problem associated with PAS systems is their extreme sensitivity to background acoustic noise and vibrations [128]. Even though PAS multi-gas analysers have been widely used in livestock studies to assess GHG emissions [113], BSFL research has yet to use them.

5.3. Electrochemical Gas Sensing

Electrochemistry or electroanalytical chemistry plays a significant role in detecting, quantifying, and monitoring target compounds across many industries, including environmental air monitoring [143]. Electrochemical sensors are a class of chemical sensors in which an electrode converts a stimulus into an electrical charge following an oxidation–reduction reaction in the presence of a target analyte for detection. The main electrochemical methods include potentiometry, conductometry, amperometry, coulometry, and capacitance [143–145]. In potentiometric gas sensing, potential differences are measured on an electrode based on Nernst's equation, which relates concentrations to potential shifts [143,145]. Conductometric gas sensors measure and detect changes in resistance to charge flow due to the presence of the target species. Amperometry/voltammetry monitors changes in current as a function of applied potential, while coulometry measures current generated as a function of time for gas detection and quantification [144].

Electrochemical gas sensors usually confer portability, ease of use, low noise, low power consumption, simplicity, high sensitivity, high selectivity, affordability, real-time studies, in situ, and rapid analyses of target species [143–145]. General drawbacks include suitability for low gas concentrations, short lifespans, problems with long-time stability, and the suitability to detect only electrochemically active gases. Gases that are not electrochemically active, such as CO_2, are measured indirectly following a reaction with another species in the sensor to generate a detectable response. It is also worth noting that these benefits and challenges associated with electrochemical sensors depend on the type of technique selected. For example, in conductometric electrochemical gas sensors, the charge concentration is not specific to any species, although it can help determine whether a threshold level has been reached. Alternatively, amperometry sensors can measure various gases simultaneously without the need to separate them first. However, some of their

limitations include a narrow temperature range for some electrolytes and stability issues over time [113,131].

Currently, many commercial electrochemical sensors are available for measuring greenhouse gases for environmental monitoring or industrial safety. Different materials, such as polymers, metals, metal oxides, semiconductors, ionic compounds, and carbon, can be used to develop electrochemical gas sensors [131,146]. For instance, metal oxide semiconductor-based gas sensors have been successfully used to detect and monitor many hazardous gases such as CO, CO_2, NH_3, N_2O, CH_4, SO_2, and O_3 at ppb and ppm levels [113,147]. Concerning gas emissions from BSFL production, electrochemical gas sensors are used predominantly to detect and quantify NH_3 [88,89,91,92]. Lindberg et al. [89] also reported using an electrochemical gas sensor system (Kitagawa gas detector) consisting of a reagent tube and a pump to measure CO_2 emissions.

Despite recent advances in detection and quantification techniques for gaseous species, choosing the right analytical method for BSFL treatment is crucial given the reported low emissions. The calibration of the instrument used, as well as its detection limit, can significantly influence the results obtained. Reference standards for gases are less readily available because their adsorption onto container walls or leakage causes them to lose stability over time. This can affect the accuracy of detecting minute analyte concentrations [148]. In addition, the relationships between breeding parameters such as feed quality, experimental scale, ambient conditions, and greenhouse gas emissions during BSFL growth have not been extensively established. Generally, researchers focus on using the larvae for waste management rather than optimising their productivity per production time. [92]. Furthermore, most studies lack real-time data that can enable the determination and understanding of the peak period of certain greenhouse gas emissions.

6. Life Cycle Assessment of the BSFL

Life cycle assessment (LCA) is a standardised method that can be used in multicriteria analyses to examine various environmental concerns such as climate change, acidification, and eutrophication [149]. The approach complies with the ISO 14040 and 14044 standards and involves the compilation and evaluation of a product's inputs, outputs, and potential environmental impacts throughout its lifetime. In general, the method consists of four interrelated phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and the interpretation of results [150,151]. It is complex and iterative but flexible enough to allow life cycle experts to modify and model their product systems [152,153].

Over the past few years, several LCA studies were conducted to evaluate the environmental profile of insect-based products. Although there is a growing interest in the ecological sustainability of edible insects, few LCA studies have been published on their products. Environmental impact assessments were carried out on the harvested or processed larvae of insects such as mealworms [154,155], house flies [156,157], and house crickets [158]. Table 4 summarises LCA studies related to the black soldier fly. The studies were conducted within the last decade, mainly in Europe. The use of BSFL as animal feed, as well as its derived products, is limited by the type of feeding material for its rearing. EC No. 1069/2009 restricts the use of food waste as feeding material, especially when it contains or is derived from catering waste [159]. However, agri-food residues are permissible. Thus, studies with food waste as the substrate (50%) have focused solely on the environmental impact of organic waste bioconversion by the BSFL with biotreated waste as the main product, though insect products could also be obtained. A BSFL value chain can generate several high-value products. Crude protein from the insect cake can be further processed to obtain bioplastic film [160–162], protein hydrolysate, and emulsifying and foaming agents. Chitin from insect meals can also be refined to produce an edible film, surgical thread, binders, and chitosan [6]. Refined fats/oil can also be refined into biodiesel and lubricating agents [7,163,164]. However, LCA has been applied to a few BSFL products.

Table 4. Overview of the LCA studies on *Hermetia illucens* considered.

Index	Author(s)	Year	Country	LCA Model	The Goal of the Study
1	Komakech et al. [165]	2015	Uganda	Attributional	Comparing the environmental impacts of different biowaste treatment technologies
2	Smetana et al. [82]	2016	Germany	Attributional	LCA of insect production and processing at an industrial scale
3	Rustad [166]	2016	Norway	Attributional	Comparing the environmental impacts of insect meal with fish meal
4	Salomone et al. [70]	2017	Italy	Attributional	LCA on the mass-rearing and food waste bioconversion by BSFL in a pilot plant
5	Mondello et al. [167]	2017	Italy	Attributional	Comparing the environmental impacts of different food waste treatment scenarios
6	Mertenat et al. [90]	2019	Switzerland	Attributional	LCA to compare the global warming potential (GWP) of BSF biowaste treatment and composting
7	Smetana et al. [83]	2019	Germany	Attributional	LCA on production stages of insect-based products and its comparison to benchmarks
				Consequential	Identifying the environmental consequences of production and consumption choices toward insect-based feed and food
8	Spinelli et al. [168]	2019	Italy	Attributional	LCA on laboratory-scale production of innovative bioplastics made from biopolymers derived from BSF proteins
9	Bosch et al. [169]	2019	Netherlands	Attributional	LCA on the production of fresh BSF larvae reared on different organic biomass resources
10	Rosa et al. [162]	2020	Italy	Attributional	LCA of BSF protein-derived bioplastic and comparison of two protein extraction protocols
11	Ites et al. [170]	2020	Germany	Attributional	Determining the environmental impact of using insects to treat food waste in a modular system
12	Guo et al. [91]	2021	China	Attributional	Revealing the environmental impact of a BSFL bioconversion plant

Regarding the LCA models applied in BSFL studies, the attributional LCA was predominant in the LCA models involved in BSFL studies. The model shows the environmentally relevant material and energy flows to and from a product or process. It allows for a comparison of products that perform a similar function [171]. On the other hand, consequential LCA describes how relevant environmental flows will change in response to possible decisions. It involves predicting the future consequences of a specific action. Thus, it requires a deeper understanding of the economic market in which the product or service is situated and its interactions with other production systems [171]. Smetana et al. [83] applied this approach to identify the environmental consequences of substituting conventional food production and consumption with insect-based feed and food. More recently, nutritional LCA has emerged as a model to integrate environmental concerns and the dietary aspects of food or feed [172]. Although many studies have been conducted on livestock growth and development on BSFL feed, no LCA study has used a nutritional approach.

6.1. System Boundaries

System boundaries clearly define what has and has not been included in an LCA and are crucial for identifying all processes relevant to that specific assessment. The phases included in the system boundary often depend on the final product considered and the LCA approach: cradle-to-gate or cradle-to-grave. A BSFL production system can consist of several operational phases due to the many potential products that can be obtained, each of which has its own production process. Figure 1 represents a generic system boundary through which the different materials, energy, emissions, and waste associated with BSFL products flow.

Generally, the upstream processes include collecting the feed or food waste materials, the transport of feed to plant, the pre-treatment of the substrate, and the insect nursery and egg hatchery. The core processes include the bioconversion activities of the larvae, harvesting, and the processing of larvae. Minimal processing includes simple operations such as drying and milling the larvae, which can be further processed and refined using various extraction methods to obtain other high-end products. The downstream processes may also include packaging, transporting the products obtained, use phase, and waste management.

The LCA studies analysed varied in terms of the phases considered in the studies. The construction and maintenance of the processing facility and the equipment involved in processing were considered in a few studies [165,166,170]. Some studies included the direct greenhouse gas emissions from the BSFL bioconversion phase as part of their

inventory [82,83,90,91]. However, they excluded direct CO_2 emissions because they are considered biogenic. The transportation of materials to the processing facility was also added in some studies [70,83,162,166,168]. Table 5 summarises the phases considered within the system boundaries of the LCA studies on BSFL. Most of the studies included all operations in the upstream and core processes. Concerning downstream units, none of the studies added the packaging phase, while only Komakech et al. [165] included distribution phases for the insect products. Frass management involved direct field application for soil-nutrient enrichment or further processing to obtain a more refined and standardized organic fertilizer in the form of compost. Wastewater management also included wastewater treatment [82,83,162,168,170] and reuse for other operations [70].

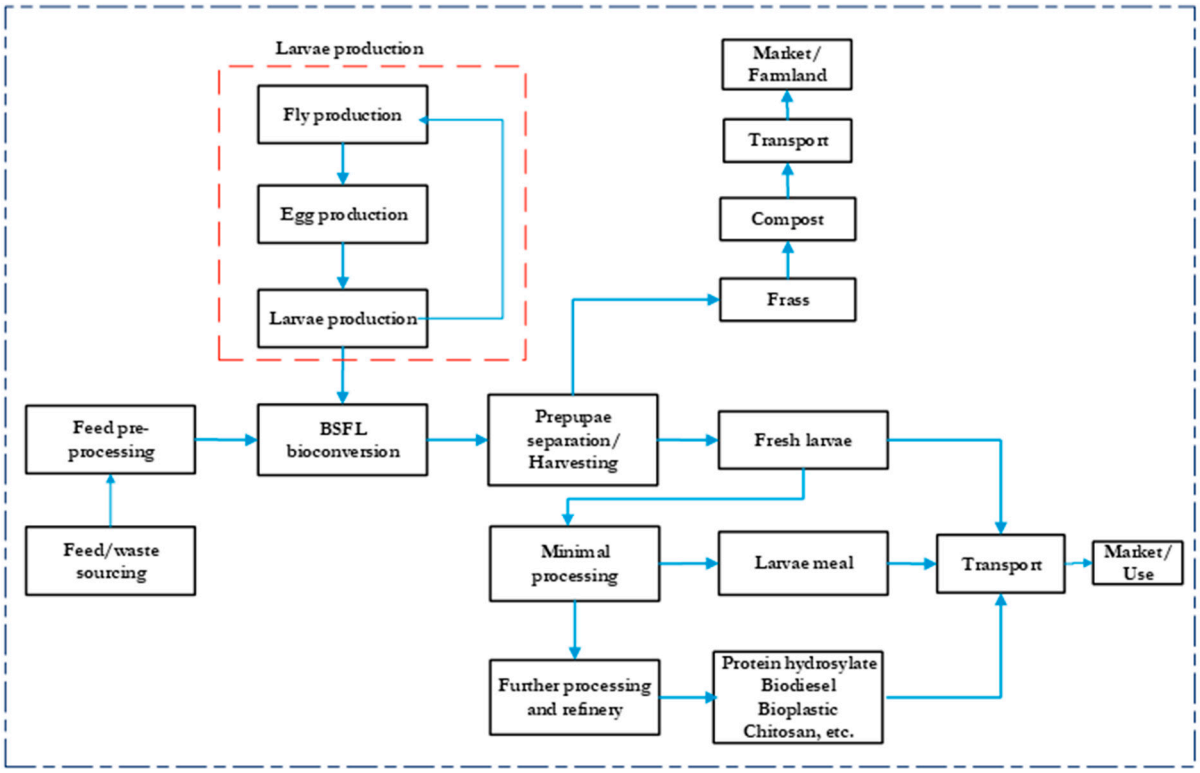

Figure 1. A generic system boundary for BSFL production and related products.

Table 5. The major phases considered in the LCA studies analysed.

Index	Fs	Tr	Fp	Lp	Bb	Lsh	Mp	Fpr	Fm	Wm
1	–	–	x	–	x	x	–	–	x	–
2	x	–	x	x	x	x	x	x	x	x
3	x	x	–	–	x	x	x	–	x	–
4	–	x	x	x	x	x	x	–	x	x
5	x	x	x	–	x	x	x	–	–	–
6	–	–	x	x	x	x	x	–	x	–
7	x	x	x	x	x	x	x	x	x	x
8	x	x	x	x	x	x	x	x	x	x
9	x	–	x	x	x	x	–	–	–	–
10	x	x	x	x	x	x	x	x	x	x
11	x	–	x	x	x	x	x	–	x	x
12	–	–	–	x	x	x	x	–	x	–

Upstream processes: Fs—feed/waste sourcing, Tr—transport, Fp—feed processing, Lp—larvae production; core processes: Bb—BSFL bioconversion, Lsh—larvae separation/harvesting, Mp—minimal processing, Fpr—further processing and refinery; downstream processes: Fm—frass management, Wm—wastewater management.

6.2. Functional Unit

The functional unit (FU) is the reference basis against which all other data in the product systems are calculated for impact assessment. It is common to use FUs as a benchmark unit for comparing the performance of different products that perform a similar function. *H. illucens* can perform different functions depending on the targeted output. Thus, several FUs were identified in the LCA studies analysed. Several studies included more than one FU to allow for easy comparisons with similar conventional products. FUs were expressed by weight in kg or ton, as shown in Table 6. In total, 63% of the functional units were directly related to insect products, while the others were related to biotreated waste.

A study's objective determines which functional unit is selected, so different study objectives led to using different functional units. Thus, in all the studies where BSFL was solely used for waste management, the authors expressed the FU as 1 ton of biowaste or food waste treated. The wide variations in the selected functional units for similar processes or products can make comparison difficult. One ton of biotreated food waste and one kilogram of a protein-concentrated meal, for example, cannot be easily compared even though BSFL's bioconversion processes generate both products.

Table 6. Functional unit (FU), allocation, secondary data sources, LCA method, and LCA software of the analysed BSFL studies.

Index	FU	Allocation	Data Sources	LCA Method	LCA Software
1	1 ton of impurity-free biodegradable waste	n.r.	literature	CML 2002 *	n.s.
2	1 kg of dried defatted insect powder 1 kg of ready for consumption fresh product	Mass [a] economic [b]	Ecoinvent literature	ReCiPe IMPACT 2002+	SimaPro
3	1 ton insect meal	economic	Ecoinvent	ReCiPe	Arda Calculator
4	1 ton of bio-digested food waste 1 kg of proteins 1 kg of lipids	Economic [c]	Ecoinvent literature	CML 2 baseline 2000 IPCC 2007 CED and CML 2001	SimaPro
5	1 ton of food waste to be treated	n.r.	Ecoinvent	CML 2 baseline 2000 CED and CML 2001	SimaPro
6	1 ton of biowaste (ww)	n.r.	Ecoinvent	IPCC 2013	SimaPro
7	1 kg of dried and pelletised organic fertilizer 1 kg of fresh BSF biomass 1 kg of protein concentrated meal 1 kg of BSF fat	economic	Agri-footprint Ecoinvent literature	IMPACT 2002+	SimaPro
8	0.403 g of bioplastic	mass	Ecoinvent	IMPACT 2002+	SimaPro
9	1 kg of fresh larvae 1 kg of larval protein	economic	Ecoinvent literature	CML	n.s.
10	0.403 g of bioplastic	mass	Ecoinvent	IMPACT 2002+	SimaPro
11	1 ton of treated food waste	n.r.	Eco-invent	IMPACT 2002+	n.s.
12	1 ton of treated food waste	n.r.	Ecoinvent	n.s	n.s.

n.r.—not required, n.s.—not specified, ww—wet weight, *BSF*—black soldier fly, CED—cumulative energy demand. * Only for eutrophication. [a] Allocation for foreground data. [b] Allocation for background data. [c] Does not apply to 1 ton of bio-digested food waste.

6.3. Allocation Criteria

Allocation in LCA allows for a fair distribution of environmental impacts between co-products derived simultaneously from the same production or process. While ISO standards recommend avoiding allocation whenever possible, it is difficult to do so in a multifunctional system such as the BSFL bioconversion system. In five out of seven LCA studies, the allocation criterion decision was made based on the economic values of the co-products when the goal was related directly to insect products. (Table 6). The high value of products such as insect meal, protein, and lipids motivated the use of economic allocation over mass and energy. In studies of bioplastics, however, the mass allocation was applied since the protein fraction from which they were derived has comparable economic value to the lipid and chitin co-products. Furthermore, since it was a biorefinery process, the goal was to optimise the yield of bioplastics [162,168]. For studies that primarily focused on the BSFL biotreatment of food waste, the allocation criteria were not necessary since the focus was on the input of the waste management process, which is seen as an end-phase activity [70].

6.4. Impact Categories

Understanding and evaluating the potential environmental impacts of a product system is part of the impact assessment phase. Emissions and resource extractions from the life cycle inventory are translated into ecological issues of concern or impact categories for straightforward interpretation. Impacts can be categorised as either midpoint or endpoint. Midpoint impact indicators focus on the potential harm to a single environmental issue. On the other hand, endpoint impact indicators show the potential impact of aggregated midpoint indicators on broader environmental issues. Several authors have reported results for different impact categories in the LCA studies analysed (Table 7). However, in terms of relative importance, all studies analysed presented results for global warming potential (GWP) or climate change either as midpoint or endpoint impact categories. Global warming potential has become a key component of most environmental impact assessment studies due to the worldwide effort to reduce greenhouse gas emissions to combat climate change. Impacts relating to energy use, land use, acidification, and eutrophication were reported in more than 70% of the studies (Figure 2). GWP was assessed in all the studies analysed, which reaffirms the global attention and efforts to address the threat of climate change. Water depletion was the least assessed impact, mainly due to the insignificant amount of water required by the insect. However, all possible impact categories must be assessed and accorded a similar level of importance since they can help stress the potential environmental gains of using BSFL products. In addition, to make a fair comparison, scores across all impact categories should be considered, as a product that performs well in one category may perform poorly in another. Different contexts, such as geographical location and time, may also influence the relative importance of impacts. For example, water depletion will be more critical in a drought-prone area. Thus, the provision of all impact results can help guide decision-making. Single scores for damage-oriented or endpoint impact categories such as climate change, ecosystem quality, human health, and resources were reported in 3 out of the 12 studies [82,162,168].

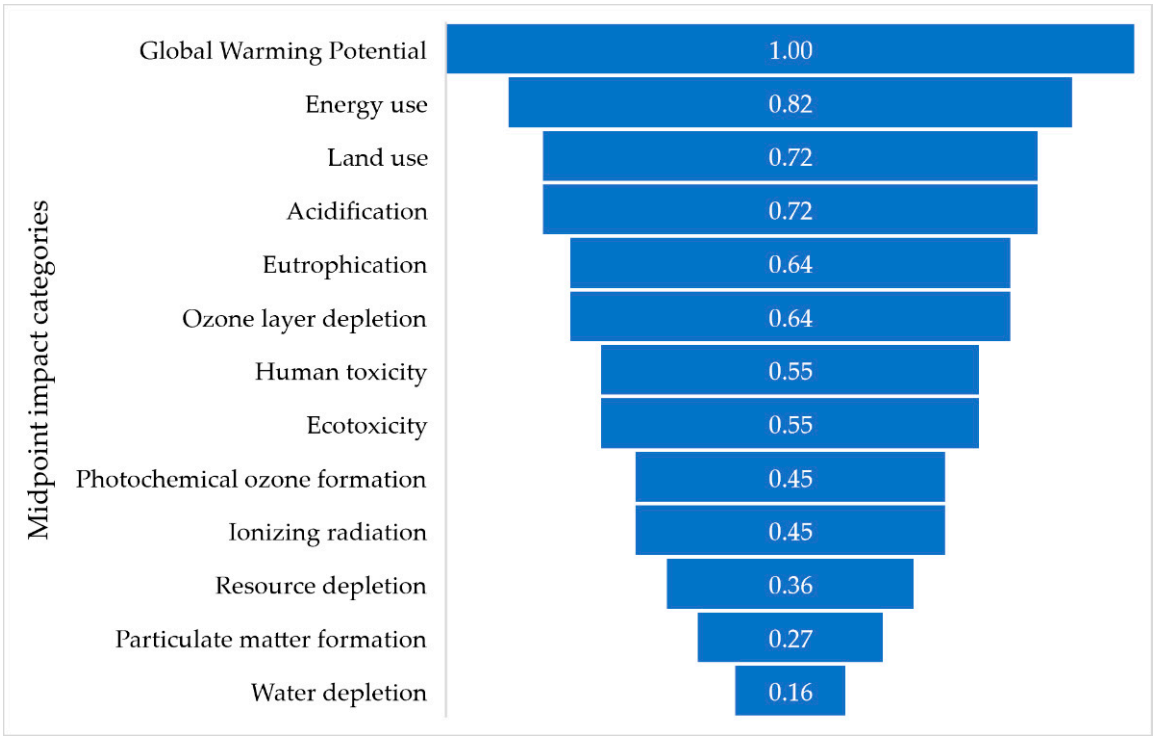

Figure 2. Relative importance of the midpoint impact categories in the studies analysed.

Table 7. Considered midpoint impact categories in the LCA studies analysed.

Index	GW	E	LU	EU	A	OD	HT	ET	POF	IR	RD	WD	PMF
1	x	x	–	x	–	–	–	–	–	–	–	–	–
2	x	x	x	x	x	x	x	x	x	x	x	x	x
3	x	x	x	x	x	x	x	x	x	x	x	–	x
4	x	x	x	x	x	x	x	x	x	–	x	–	–
5	x	x	x	x	x	x	x	x	x	–	x	–	–
7	x	x	x	–	x	x	x	x	–	x	–	x	–
8	x	–	–	–	–	–	–	–	–	–	–	–	–
9	x	x	x	–	–	–	–	–	–	–	–	–	–
10	x	x	x	x	x	x	x	x	x	x	–	–	–
11	x	x	x	–	x	x	–	–	–	–	–	–	–
12	x	–	–	x	x	–	–	–	–	–	–	–	x

GW—global warming, E—energy use, LU—land use, EU—eutrophication, *A*—acidification, OD—ozone layer depletion, HT—human toxicity, ET—ecotoxicity, POF—photochemical ozone formation, IR—18 ionizing radiation, RD—resource depletion, WD—water depletion, PMF—particulate matter formation.

6.5. LCA Methods, Databases, and Software

In forty-five per cent of the studies, the classification and characterisation of impact assessment were based on the IMPACT 2002+ method. The IPCC methods were also used in most studies to determine the global warming potential or climate change. Other studies used the ReCiPe [82,166], CML 2 baseline 2000 [70], and CML 2002 [165] methods for their impact assessment.

For most studies, the foreground data came from primary data collected over a specified period, except for Bosch et al. [169], where only secondary data were used. Regarding secondary databases consulted for characterisation factors and inventory completion, the Ecoinvent database was the most predominant (Table 6). The data were mainly used to model background processes such as fuel and electricity production, input transportation, and input production. Additional relevant data sources included Agri-footprint [83], which provides information on agricultural products, and peer-reviewed scientific literature [70,82,165,169].

The SimaPro software was used in 86% of the studies when the software was specified. This commercial tool helps in modelling and evaluating the environmental impacts of a product or process and makes several databases available, including Ecoinvent, and many impact assessment methods for midpoint and endpoint impact categories. Rustad [166] reported using the Arda Calculator software developed by the Programme of Industrial Ecology at the Norwegian University of Science and Technology to perform the LCA analysis. The software also embedded the Ecoinvent database and the ReCiPe impact assessment method.

7. Impact Assessment

7.1. GWP for Biowaste Treatment by the BSFL

Seven of the twelve analysed LCA studies on BSFL reported results relating to the GWP associated with BSFL biowaste treatment. Food waste collected from various sources was the main type of organic waste. However, Ites et al. [170] also reported GWP results for specific waste materials such as brewery grains, potato peels, and expired food products. Figure 3 shows the calculated GWP scores per ton of biotreated waste from the LCA studies analysed.

The impact scores in LCA heavily depend on the systems included in the system boundary. Scores are generally higher for the functional unit if all processes and direct emissions are considered. For instance, Komakech et al. [165] and Guo et al. [91] reported relatively low GWP scores of 12.40 and 17.36 kg CO_2 eq./ton FU, respectively, mainly because several other impacting phases, such as substrate collection, transport, pre-treatment, and larvae production, were excluded from the system boundary (Table 5). On the other hand, Smetana et al. [83] found a very high impact score of 877 kg CO_2 eq./ton dried

organic fertiliser because they included the materials and energy relating to additional phases such as the construction of the processing facility, larvae production, and further frass processing to obtain the final dried organic product.

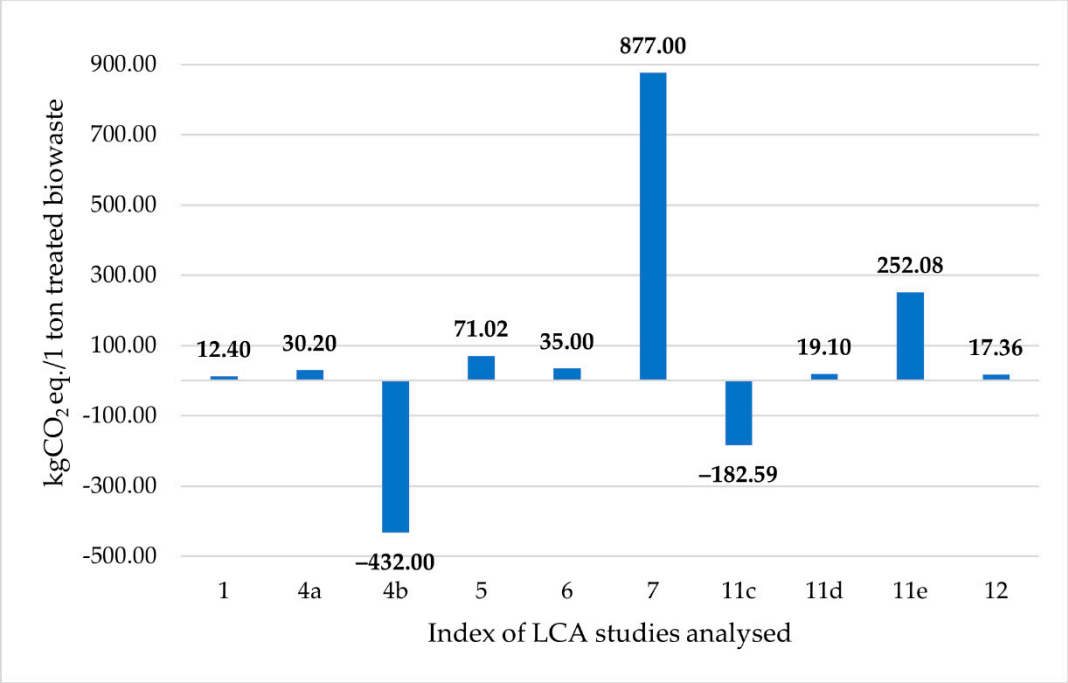

Figure 3. GWP results reported in LCA studies on biowaste treatment using the BSFL: 4a is without avoided products, 4b is with avoided products, 11c is brewery grains as substrate, 11d is expired food as substrate, and 11e is potato peels as substrate.

Additionally, it is worth noting that some studies did not include direct greenhouse emissions from BSFL due to the perceived low emissions associated with the insect and the unavailability of specific inventory data at the time of the study [70,166]. In contrast, other studies relied on the direct emissions reported in the literature for other insects, such as *Tenebrio molitor*, *Acheta domesticus*, *Locusta migratoria*, *Pachnoda marginata*, and *Blaptica dubia*, as background data for their inventory list [70,82,83]. However, the cumulative direct nitrous oxide and methane emitted during the BSFL bioconversion activities were included as foreground in some studies [90,91].

Regarding the most impactful phases and processes, most studies cited direct emissions from the BSFL bioconversion phase and energy consumption as having the most influence on the GWP score. Although direct greenhouse emissions are generally low and less impactful, Mondello et al. [167] found that electricity consumption and GHG emissions from the BSFL bioconversion phase contributed 56.4% and 24.2% to the total GWP score. Salamone et al. [70] reported similar findings, citing the most significant contributions as the transportation of food waste to the facility (18%) and the composting and larval drying phase (75%). GHG emissions from bioconversion (57.2%) and electricity consumed (16%) contributed primarily to impacts in the latter step. Mertenat et al. [90] attributed 72% of the total GWP to direct emissions from the BSFL treatment facility and 19% to indirect emissions from electricity consumption. Guo et al. [91] also reported 17.24 and 72.81 kg CO_2 eq./ton FU as direct emissions and electricity consumption contributions to the total GWP score.

Concerning the inclusion of avoided products, Salomone et al. [70] found a net positive GWP of −432 kg CO_2 eq./ton biotreated food waste when avoided N fertilisers and soy meal products were included as substitutes in compost and dried products for BSFL larvae, respectively. Although avoided waste for brewery grains and potato peels and the waste

treatment of expired food products were included in the analysis by Ites et al. [170], only the GWP of the system fed with brewery grains had a total net positive impact score of −182.59 kg CO_2 eq./ton FU. Furthermore, Guo et al. [91] and Mertenat et al. [90] also included avoided products in the utilisation of organic material and fish meal production and transport, respectively. In principle, avoided products are used for system expansion, an alternative to allocation. In system expansion, co-products are considered options for other products on the global market. An impact credit is given to the principal product by substituting the co-product for this product [173]. This reduces the impact of the main product and can lead to a net positive impact score. System expansion is usually linked to the consequential LCA approach. Co-products can often perform different functions, so results depend on the commercial products or processes substituted or avoided during modelling.

7.2. GWP for Insect Products

Fifty-eight per cent of the LCA studies analysed reported GWP scores expressed in terms of different functional units, such as fresh larvae, insect protein, and lipids. Varying GWP scores were obtained for the different products (Table 8), mainly due to the different processing methods included in the studies. Generally, higher impact scores were reported for refined products of higher economic value [162,168]. The main contributors to the GWP were contributions from feed production, collection, transportation, feed pre-treatment, biomass processing and biorefinery. In terms of GWP, several studies reported BSFL products to be comparable to conventional commercial products on the market. Although BSFL protein reported lower GWP scores than protein sources, such as egg protein concentrate, whey concentrate, and microalgae, other protein sources such as fish meal and soybean were less impactful [70,83]. Salomone et al. [70] also reported a 7.4% increment in GWP when rapeseed lipid was compared to BSFL lipid.

Table 8. The global warming potential scores for different insect products.

Index	GWP, kg CO_2 eq.	Functional Unit
2	1.36–15.1	1 kg of insect protein meal
3	0.17	1 kg of insect meal (wet weight)
4	2.1	1 kg of insect protein (dried larvae)
	2.9	1 kg of insect lipid (dried larvae)
7	5.3	1 kg of insect meal (defatted protein concentrate)
	1.16	1 kg of insect puree (fresh insect production)
8	1100	1 kg of bioplastic obtained from BSFL protein
9	1	1 kg of fresh larvae
	19	1 kg of protein (food) [a]
	3	1 kg of protein (feed) [a]
	6	1 kg of protein (residue) [a]
10	698	1 kg of extracted protein (chemical extraction)
	1884	1 kg of extracted protein (enzyme-assisted extraction)

[a] drying phase excluded. *Food*—BSFL reared on products humans can consume; *feed*—BSFL reared on livestock feed; *residue*—BSFL reared on organic material not used as food or feed.

Protein was the predominant insect product of interest in most of the LCA studies analysed due to the promising potential to substitute some conventional protein sources deemed to be less environmentally sustainable. The insect biomass's protein content mainly depends on the insect diet used for rearing. Although low-quality feeding material is cheaper and often less impactful, protein quality and yield may be negatively affected. As a result, using a low-quality insect diet can lead to a potential increase in impacts since more collection, transport, and feed pre-treatment is required to obtain the same protein yield compared with using a higher quality feed [82,169]. Bosch et al. [169] reported a lower GWP score (68%) for proteins obtained from BSFL reared on residual materials than edible food products for humans. Other factors, such as the extraction methods applied to

obtain the insect products of interest, can also influence the GWP. Rosa et al. [162] reported that using a chemical extraction method was less impactful than using an enzyme-assisted protocol to extract BSFL protein.

7.3. Energy Use

Energy consumption is one of the major environmental concerns related to BSFL bioconversion systems [70,83]. Table 9 shows the different energy use results reported in the analysed BSFL studies. Generally, higher energy use was reported in studies that included downstream operations such as drying and other biorefinery processes within the system boundaries (Table 5). Thus, energy use was relatively lower for biotreatment than for insect products such as protein. Heating is required to maintain the ambient temperature conditions of the insect during the production and bioconversion phases. However, this depends on the climatic conditions of the plant location. Adult BSFL also requires adequate lighting for mating, often provided through electrical energy. Most downstream processes, such as biomass drying and milling, consume a significant amount of energy. Similar findings were also reported by Onincx and De Boer [154] and van Zanten et al. [156] during the rearing of mealworms and house flies, respectively. The type of feeding material can also significantly affect energy consumption due to high energy use in production [83,169,170]. Impacts reduce by 85% when residual materials are used to rear BSFL instead of food fit for human consumption [169].

Table 9. Impact results for energy and land use reported in the different LCA studies analysed.

Index	MJ	m^2 Arable	FU
1	15.12	–	1 ton of food waste
2	21.20–99.60	0.03–7.03	1 kg of insect protein meal
4	215.30	0.67	1 ton of food waste treated
	15.10	0.47	1 kg of protein (dried larvae)
	20.80	1.38	1 kg of lipid (dried larvae)
5	772.62	0.89	1 ton of food waste to be treated
7	13.00	0.47	1 kg of insect fertilizer (dried and pelletized)
	61.29	1.38	1 kg of lipid
	17.90	0.48	1 kg of puree (fresh insect production)
9	8.00	2.00	1 kg of fresh larvae
	174.00*	67.00	1 kg of protein (food) [a]
	84.00*	3.00	1 kg of protein (feed) [a]
	26.00*	0.00	1 kg of protein (residue) [a]
10	15.06	0.12	1 g of extracted protein (chemical extraction)
	40.26	0.33	1 g of extracted protein (enzyme-assisted extraction)
11	−3067.66 *	−477.20	1 ton of brewery grains treated
	2846.94 *	−1.16	1 ton of potato peels treated
	−23.49 *	−0.61	1 ton of expired food treated

* Results relate to only primary energy. [a] drying phase excluded. *Food*—BSFL reared on products humans can consume; *feed*—BSFL reared on livestock feed; *residue*—BSFL reared on organic material not used as food or feed.

Regarding energy use for different waste management systems, including the BSFL biowaste treatment, Komakech et al. [165] reported that anaerobic digestion and composting consumed less energy than the BSFL compost treatment, while vermicomposting consumed more. In contrast, Mondello et al. [167] concluded that the BSFL biotreatment of food waste was more energy-efficient than landfilling, incineration, composting, and biogas scenarios.

Transitioning to alternative energy sources such as renewable energy can mitigate some of the impacts related to energy consumption. Salomone et al. [70] performed a sensitivity analysis on alternative energy sources for the drying process. They found that using photovoltaic and natural gas was more efficient—45.58% and 4.65%, respectively—than the baseline scenario of electrical energy from the Italian mix. Similarly, Smetana et al. [83] found that using long-term photovoltaic energy could reduce impacts by 25%. Thus, there is a need to consider renewable energy sources for operating a BSFL facility to save on energy consumption.

7.4. Land Use

Land use change and land occupation constitute two aspects of land use. The concept of land use change refers to the human transformation of one land use type into another. Conversely, land occupation is defined as the continuous use of a land area for a specified kind of land use for a particular period. Both scenarios can result in significant ecological concerns, such as biodiversity loss, for example, when a forest is used for building construction. However, there could be a positive effect on the environment in some cases when transformation leads to eco-friendly outcomes [174].

Land use is an impact of great interest in the agri-food sector due to the alarming rate of forest conversion into farmlands to meet human and livestock nutritional needs. Land use can play a critical role in selecting more environmentally sustainable food sources, particularly protein production. Due to its relative land efficiency, insect production has a major advantage during periods of agricultural land scarcity. Protein and lipids derived from the BSFL reared on food or feed waste materials proved far more efficient than conventional sources such as soya meal and rapeseed in terms of land use [70,169]. However, land use scores were higher when BSFLs were fed on food or feed fit for human and livestock consumption [169]. Table 9 summarises the impact scores of land use from the different LCA studies on BSFL analysed, expressed in corresponding functional units. Land use scores were lowest when BSFL was used for the biotreatment of food waste and higher for refined BSFL products such as proteins and bioplastics. Considering the avoided waste treatment of expired food products and the avoided waste of brewery grains and potato peels, net positive land use scores were reported by Ites et al. [170]. BSFL biotreatment required less land than landfills and organic waste incineration treatment [167].

8. Conclusions

There is an increasing interest in *H. illucens* due to its ability to produce high-value commercial products with high environmental and economic sustainability potential. However, like other production systems, the ecological aspects of the *H. illucens* value chain should be considered when advocating insect product use. A comparison of the environmental sustainability assessment of insect products with other conventional products, such as meat, in proper contexts is also much needed, considering the wide variations in impact scores for these products.

Studies on greenhouse gas (GHG) emissions associated with BSFL rearing and bioconversion activities are limited. This review summarised the available studies on detecting and quantifying greenhouse emissions from BSFL biotreatment while highlighting the strengths and limitations of the methodologies and analytical techniques employed in the studies. Traditional chromatographic methods have been widely used in measuring gas emissions from BSFL biotreatment. Although these analytical techniques provide a more accurate measure of the gases, they are expensive, laborious, and do not provide real-time data. Thus, there is a need for more electrochemical sensors, as they are cheap, sensitive, easy to install, and allow for real-time gas monitoring, especially via wireless data transmission to a user interface. Thus, these gas sensors can be installed to monitor air quality in a commercial BSFL plant. However, the detection electrode, detection limits, accuracy, and robustness of the sensors should be considered during selection.

While most studies report GHG emission data from batch samples, these data do not provide insight into how various parameters influence emissions during BSFL biotreatment. However, it is evident that the influence of several factors, such as insect diet quality and other breeding conditions, on GHG emissions, especially nitrous oxide, remains unclear and needs to be thoroughly investigated. Therefore, there should be more studies focused on continuous gas monitoring for BSFL biotreatment to increase our understanding of the relationship among the factors affecting gas emissions. An accurate assessment of GHG emissions is also critical to evaluating the environmental sustainability of BSFL's performance using the life cycle approach. To reduce data uncertainty and variability in gas emissions estimates during BSFL biotreatment, extensive domain knowledge is

required to model for the unavailable primary data. Understanding the effect of the various parameters on gas emissions is fundamental to predicting the type and amount of gas to be emitted. In addition, attempts must be made to establish a correlation between the various factors influencing gas emissions and the BSFL biomass quality and yield. Moreover, understanding the influence of different factors and conditions on gas emissions will help suggest tailormade and feasible mitigation strategies to reduce environmental impacts.

Several life cycle assessment studies have been conducted on BSFL production and related products. However, there is no widespread consensus on the best way to perform a life cycle assessment of BSFL production. Wide variations in the choice of the functional units, system boundaries, allocation and system expansion criteria, and the impact assessment methods were observed in the studies analysed. Currently, there is no product category rule for insect products. PCR provides specific guidelines for conducting an LCA for products with similar functionality. This allows LCA practitioners to generate consistent and comparable results for products in the same category. Due to the multifunctionality of the BSFL value chain, a consensus on methodological approaches for BSF products must be reached in the future to eliminate any form of bias in the environmental impact assessment.

Attributional LCA was predominant since it is relatively easy to perform, though a consequential LCA on BSFL products has been performed. For a better understanding of how different modelling approaches contribute to evaluating future mitigation strategies, more complex predictive models, such as the consequential approach, should be investigated. More LCA studies on the various commercial products that can be derived from BSFL bioprocessing, such as biodiesel and edible films, should be conducted to allow for a more holistic evaluation of the BSFL value chain, as well as a comparison with traditional sources. There is also no available study on any nutritional LCA on BSFL feed for livestock and pets. Considering that the primary function of BSFL feed is to provide nourishment, it would be interesting to establish a quantifiable relationship between the factors influencing the nutritional value of insect meal and its environmental impacts.

Evidently, GWP was the most assessed impact in the studies analysed. However, other impact categories, such as water depletion, must be attributed with a similar level of importance and reported because, though some of these impact categories may seem less significant in BSFL production, providing their impact scores emphasises the degree of benefits from using BSF products in comparison to alternative products. Moreover, it permits a fairer comparative assessment between BSF products and other commercial products since their environmental performance may differ significantly in different impact categories. Although most studies indicated that the bioconversion and processing phases were the most impactful, the considerable variations in GWP, energy use, and land use results were mainly due to data quality and methodological differences, such as phases included in the system boundaries and assumptions. Access to LCA studies that are complete and accurate can increase trust, which can guide policymakers, producers, and consumers in making informed decisions about *H. illucens* products.

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