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# Recent Developments, Challenges, and Environmental Benefits of Using *Hermetia illucens* for Bioenergy Production Within a Circular Economy Approach

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**Abstract:** This study proposes a novel integrated biorefinery approach that combines *Hermetia illucens* (Black Soldier Fly) larvae treatment, anaerobic digestion (AD), and hydrothermal carbonization (HTC) to enhance the valorisation of fat-rich food residues. The process was designed to improve biogas yields while mitigating the inhibitory effects of lipid accumulation in AD systems. Results from larval bioconversion showed effective fat removal and a promising potential for protein and biomass valorisation. Downstream integration with AD and HTC enabled thermal self-sufficiency, enhanced energy recovery, and improved digestate dewaterability. Additionally, HTC process water recirculation to the AD unit was evaluated, considering its acidic nature and impact on biomethane production. A thermally integrated process flow was proposed, enabling efficient heat exchange and reduced external energy input. The overall system allows for multi-product recovery—including biogas, hydrochar, and larval biomass—offering a sustainable pathway for circular bioeconomy applications. This study illustrates the feasibility of a synergetic process chain that maximises energy recovery and resource efficiency from food industry waste streams.

**Keywords:** biorefinery; circular economy; bioenergy; sustainability; biomethane; *Hermetia illucens*

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## 1. Introduction

A rapid transition from fossil fuels to renewable energy sources is essential to mitigate the impacts of climate change [1]. The International Energy Agency (IEA)'s Sustainable Development Scenario (SDS) outlines a pathway to limit global temperature increases to well below 2 °C above pre-industrial levels. By 2040, approximately 85% of global electricity generation should be derived from low-carbon technologies [2,3].

Among the renewable alternatives, biofuels produced from agri-food residues and waste have emerged as a promising solution. As a result, agri-food waste has become a leading alternative energy source, effectively addressing economic and environmental challenges [4]. In this context, the use of insects for bioconversion is gaining attention, especially for their capacity to transform organic waste into valuable biomass. *Hermetia illucens* (Linnaeus, 1758), commonly known as the "Black Soldier Fly" (BSF), is a Diptera of the Stratiomyidae family, characterised by its black body, the armour-like thoracic spines of the adults, and the striped larvae that resemble soldiers' uniforms [5,6]. Furthermore, adults have an appearance that mimics the wasp *Trypoxylon politum* (Say, 1837). Despite their intimidating appearance, BSF larvae (BSFL) are harmless to humans. Native to the neotropical regions of the American continent, *H. illucens* is now considered cosmopolitan due to trade, migration, and the increasing interest in experimental and "industrial" rearing. It is currently found in tropical, subtropical, and temperate zones between the latitude 40° South and 45° North [7–9].

*H. illucens* has a holometabolous post-embryonic development (complete metamorphosis). The entire development, from the egg to the adult stage, lasts around 45 days and involves six larval instars and a passage through a pupal stage [10]. The larval stage is characterised by intense feeding and body mass gain, while the adults can be non-feeding, even if their reproductive performance is increased by the availability of some sugar solutions [11]. This means that almost all the energy and nutrients required for development and reproduction are acquired as larvae. The larvae are saprophagous and photophobic, living and feeding on organic matter from animal or vegetal sources during the decomposition process [12]. Even if it is well known that among the substrates used by this species are included carrion, garbage, and many other potentially microbiologically unsafe materials, *H. illucens* is considered a "non-pest", and it does not appear in the list of disease-carrying organisms or vectors for pathogens. Indeed, due to its oviposition habit, this species does not spread pathogens from waste, as female BSFs oviposit only around the edges of the larval feeding substrate rather than directly on the feed itself [12]. *H. illucens*, as a decomposer, competes with other organisms that colonise organic waste in various ways. For example, it is often reported in the literature that the presence of *H. illucens* in a substrate inhibits the laying of *Musca domestica* (Linneus, 1758) eggs, but Miranda et al. [13] show, in their research, that this depends on the age of the substrate (fresh or not) and the level of colonisation the competitor has reached in that substrate. *H. illucens* larvae have difficulty competing with the larvae of *Megaselia scalaris* (Loew, 1866) [14]. Generally, *H. illucens* competes well against bacteria and fungi, as its larvae express a broad spectrum of antimicrobial products. This capacity is essential for *H. illucens*'s protection from infections caused by opportunistic microorganisms in their growth medium [15] and for efficiently reducing *Salmonella* spp. [16].

Thanks to its ability to digest various types of organic waste, high adaptability in food sources, rapid growth and reproduction, short life cycle, and antimicrobial activity, *H. illucens* has attracted growing interest for farming. Its competitive advantage over other insects, absence of anthropophilic behaviour, and low-cost, space-efficient rearing make it an ideal candidate for sustainable waste management systems and for trying to scale up at an industrial scale to reduce and reuse waste generated by different human activities [17–22]. In fact, *H. illucens* is considered a highly effective tool in waste processing and management, and it is considered the optimal insect to give value to different kinds of wastes in the framework of a circular economy [12,23,24] due to the promising results in converting different organic agri-food industry residues into an insect biomass rich in protein and lipids. The larvae could be potentially utilised as an alternative protein source for producing animal feed for the fish, poultry, and pig industries, and the remaining industry residue can also be further processed to be used as fertiliser. Therefore, larvae can not only be useful in reducing the volume and mass of residues, making them easily manageable, but they can also be a source of high-added-value active molecules with interesting properties [25,26]. *H. illucens* larvae could be used not only to valorise agri-food industry waste but also to take advantage of by-products of fermentation to obtain other interesting compounds, such as bioactive peptides [27], polyunsaturated fatty acids, which can be found in the larvae at a percentage of 7% [28], and antioxidants peptides [29]. These natural bioactive compounds are particularly interesting for different applications, including both therapeutic and cosmetic applications (Figure 1) [30,31].

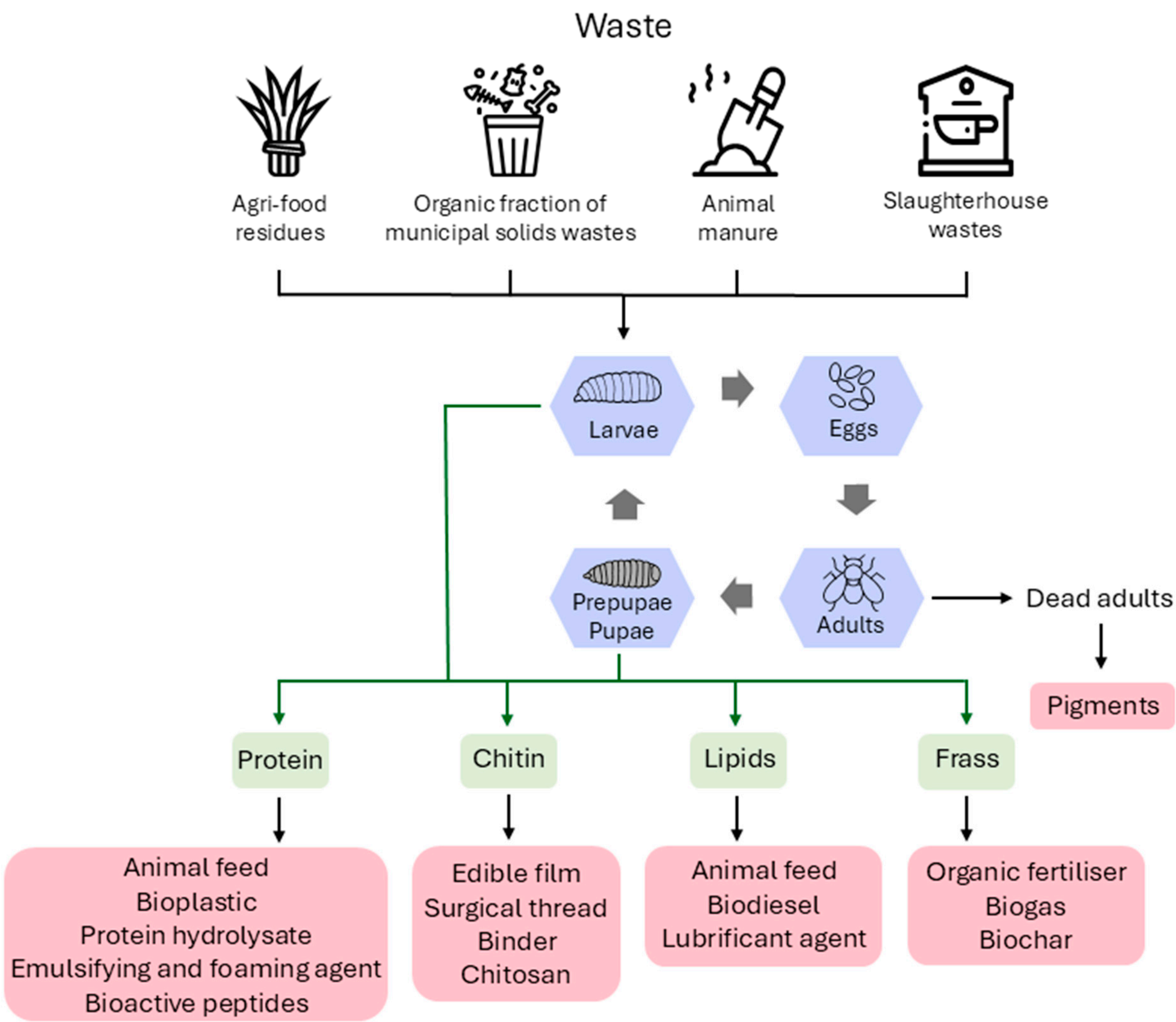


**Figure 1.** A scheme of the use of *Hermetia illucens* to produce added-value products (modified from [31]).

Besides theoretical potentiality, the insect breeding sector is relatively new and requires new regulations. For this reason, the EU has begun to address the issue, also considering the new legislation that governs the circular economy. The framework is still in progress, but the fundamental part has been issued. Most of this information can be obtained through the International Platform of Insects for Food and Feed (IPIFF), which has issued a "Guide on Good Hygiene Practices for EU Producers of Insects as Food and Feed". The guide update, released in November 2024, reports several considerations and data about the legislation concerning insect rearing in the EU [32]. Legislative texts are mostly known as the "General Food Law" (Regulation No 178/2002) and the "Hygiene Package" (e.g., Regulation No 852/2004). Insects reared within the EU belong to the "farmed animals" category (animals that are kept producing food, feed, or other derived products, such as wool or hides), as defined in the EU "Animal By-Products" (ABP) legislation (i.e., Article 3(6)16 of Regulation (EC) No 1069/2009). This category of animals needs to be subjected to a restricted diet. They may only be fed with materials of vegetal origin. However, some exceptions are permitted for animal origin materials, such as milk, eggs and their products, honey, rendered fat, and blood products from non-ruminant animals. Feeding farmed animals with other slaughterhouse- or rendering-derived products, manure, or catering waste is prohibited. The same ban applies to the use of unsold products from supermarkets or food industries (e.g., unsold products resulting from manufacturing or packaging defects) that contain meat or fish. These restrictions are applied independently of the destination of the insect-derived products, including feed for pet food, animal fur, or technical uses such as biofuel production, cosmetics, and biochemistry. Furthermore, insect producers must ensure that their animals are in good health to prevent the spread of diseases among their production flock. To this end, EU policymakers have established the responsibilities of animal breeders around health and biosecurity in the so-called "EU Animal Health Law", Regulation (EU) No 2016/429, on transmissible animal disease [32]. Currently, the possible use of insects as food and feed in the EU is reported in the scheme below (Figure 2).

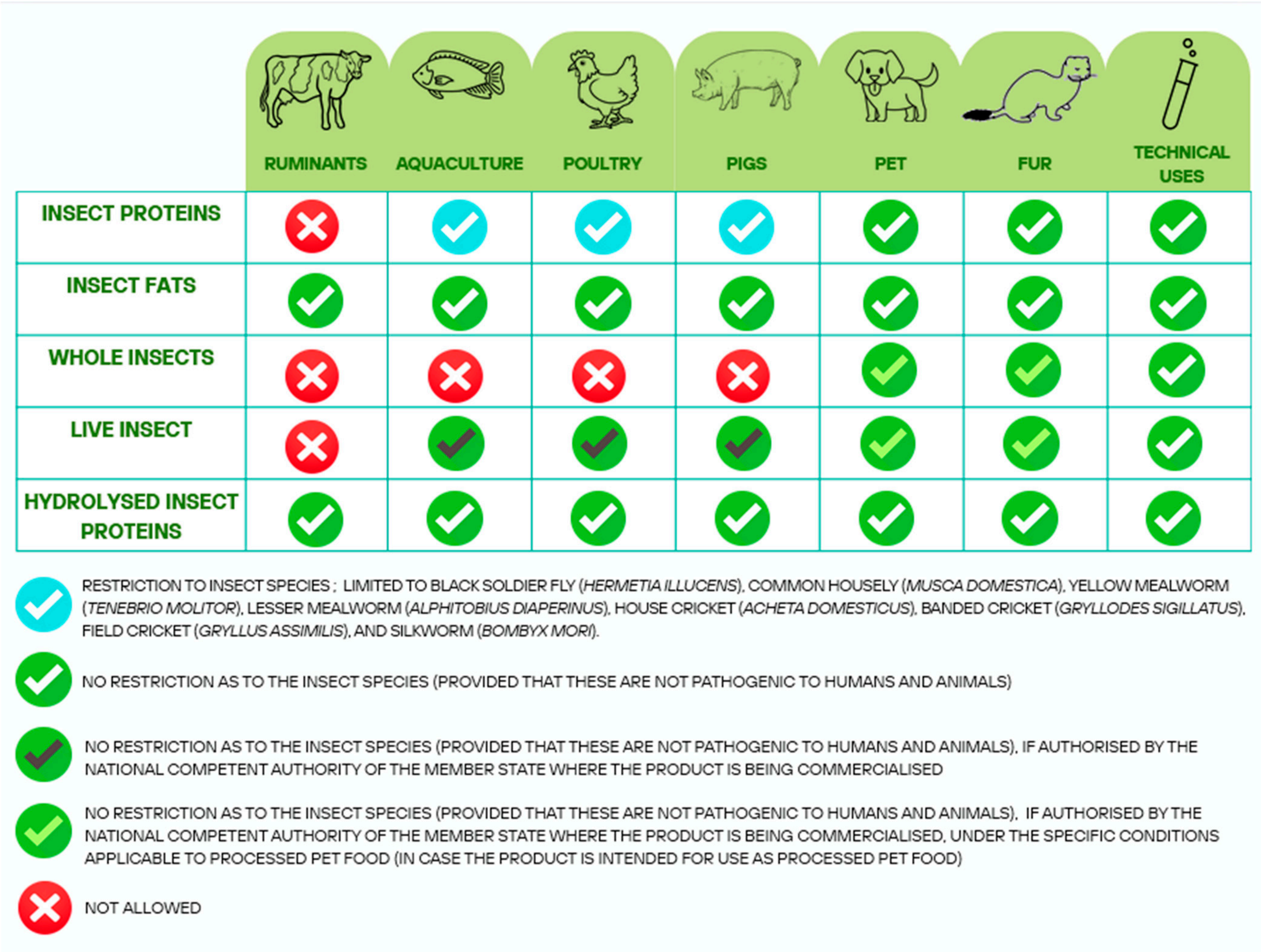


**Figure 2.** Insect as food and feed: use allowed by EU legislation. Modified from [32].

Further clarification is also needed concerning the regulation of insect frass, considering the value of this by-product, which can be used as fertiliser and close the cycle of the circular economy by reintroducing relevant nutrients and organic matter into the soil. The Commission Regulation (EU) 2021/1925 defined insect frass as the "mixture of excrements derived from farmed insects, the feeding substrate, parts of farmed insects, dead eggs and with a content of dead farmed insects of not more than 5% in volume and not more than 3%

in weight". But even with the definition, the regulations do not specify in which category the insect frass is inserted, and different national authorities consider it differently.

A literature review of 111 scientific papers from the SCOPUS database identified the key mechanisms through which the circular bioeconomy enhances food safety, reduces environmental impact, and improves energy efficiency in the food industry [33]. This sector currently accounts for about 30% of global energy use, including energy for processing, heating, refrigeration, drying, packaging, and transportation [34,35]. A circular economy approach can improve energy efficiency while producing bio-based energy sources like biofuels, offering a sustainable alternative to fossil fuels and contributing to the reduction of emissions [33].

In light of these considerations, this paper investigates whether, at a regional scale, integrating food processing with residual biomass-based energy production can generate sufficient energy to support food industry operations while reducing emissions across the supply chain. Although *H. illucens* larvae have been extensively studied for their roles in waste management and protein production, their potential for bioenergy generation remains underexplored.

This study aims to address this gap by evaluating not only the technical and practical aspects of *H. illucens*-based energy solutions but also their potential environmental impact. Specifically, it explores the following research questions: (1) Which uses of *H. illucens* larvae and which types of organic residues remain largely unaddressed in the current literature despite their potential for energy recovery? (2) Can such uses be integrated into an innovative, regionally scaled biorefinery system? (3) What advantages and barriers exist for the implementation of this approach in terms of sustainability, technical feasibility, and regulatory compliance? Therefore, the objective of the present work is not to compare the effectiveness of different valorisation technologies but rather to explore how to integrate diverse technologies in a novel and effective manner in order to maximise energy production while minimising potential environmental impacts.

Despite current legislative constraints, a key goal of this work is to contribute to the ongoing revision of regulations that promote broader sustainability across the system, focusing exclusively on non-food applications to eliminate risks to human or animal health. Supporting such regulatory evolution is essential to fostering innovation and guiding the responsible development of this emerging sector, ensuring alignment with long-term environmental and public health objectives.

## 2. Materials and Methods

To achieve the aforementioned objectives, this study integrates a comprehensive literature review, supporting experimental trials and developing a process layout to outline an effective biorefinery system. This multi-pronged approach provides theoretical grounding and practical insights into the potential integration of insect-based biomass into sustainable energy systems.

### *2.1. Literature Review*

This section describes the methodology used for the literature review, following the structured approach of Tranfield et al. [36]. The review has been conducted in three stages to investigate the role of the circular economy in developing sustainable food systems. SCOPUS has been selected as the primary database, as it offers broader coverage than the Web of Science for the research topic. Articles published between January 2011 and January 2025 were retrieved using initial search terms such as "*Hermetia illucens*", "energy", and "biofuel". The search was further expanded by reviewing reference lists and citations from the relevant articles. To finalise the sample, a range of inclusion and exclusion criteria were selected: book chapters, conference proceedings, review articles, and papers not directly addressing the link between *H. illucens* and energy production were excluded. Screening was conducted based on titles and abstracts. Relevant articles were systematically tabulated, capturing key information such as titles, authors, publication year, main products obtained, issues investigated (economic and environmental), and countries where the studies were conducted.

### *2.2. BSFL Rearing Experiments*

This approach aims to assess the technical feasibility and environmental implications of incorporating insect-based biomass processing into regional bioenergy systems using meat residues. *H. illucens* were obtained from a colony kept at the Università Cattolica del Sacro Cuore, campus of Piacenza, in Italy (45.037498 N, 9.727744 E). The insects were reared in a climate-controlled room, with mechanical ventilation, maintained at 28 ± 2 °C and approximately 60% relative humidity (RH), under an artificial lighting schedule of 16 h light and 8 h dark (light model BSF-4C-200-3030: JMGreen Black Soldier Fly Breeding LED 150 W by Evo Conversion System, LLC, College Station, TX, USA) [14].

Adults were reared in a 1.5 × 1.5 × 1.5 m net cage and fed with sucrose water solution. Egg collection was performed using a small white plastic bar with 3 mm curves as oviposition sites, placed inside a black recipient. A standard diet, consisting of chicken moistened with water (40:60 ratio), was used as an attractant. Bars with 24 h laid eggs were collected and transferred to plastic boxes (20 × 12 × 11 cm) with ventilated lids containing the standard rearing substrate. At 3 days old, larvae were collected and assigned to different experimental treatments. The remaining larvae were moved to bigger plastic boxes (37 × 28 × 12 cm) and fed the standard diet until the prepupal stage for colony maintenance.

#### 2.2.1. Diets and Experimental Design

For the experiments, ham residues were received from local producers. Due to its seasoning, this by-product consists of raw ham pieces with variable dimensions and compositions, mainly containing large portions of fat and high salt content. In general, for each 100 g of ham, there are 2.7 to 6.7 g of chlorides, including NaCl, and the estimated final salt content is 4.3 to 6.1 g, with a resulting pH between 5.40 and 6.30. This material was first triturated into small pieces before being provided as a diet for the larvae. A proportion of the raw ham was treated with hot water according to the following procedure: triturated ham and distilled water were mixed (1:1 ratio) and transferred to plastic containers (8.5 × 8.5 × 5.5 cm). The boxes were sealed in plastic bags and kept submerged in a water bath at 20 or 35 °C for 24 or 48 h. The temperature was monitored with Testo 174H data loggers (NTC sensor, ranging from 0 to 100% RH with an accuracy of ±3% RH, and −20 to +70 °C with accuracy of ±0.5 °C, Testo S.p.A., Settimo Milanese, Italy). After 24 and 48 h, the contents of each box were sifted to separate the ham from the non-absorbed water.

We performed four experiments to evaluate the suitability of ham for larval rearing. All the experiments were carried out with 3-day-old larvae, lasting 10 days, and in each experiment, each thesis was replicated four times.

Experiment 1 (only raw ham as the diet): Triturated raw ham (20 g) was placed into a plastic cylinder (5 cm diameter, 8 cm high) with a ventilated lid, and 20 or 100 larvae were placed inside (larval density: 1 or 5 larvae per $cm^2$). Larvae of the control groups received the standard diet (chicken feed, as reported above).

Experiment 2 (only pretreated ham as the diet): The ham treated at different conditions was provided to the larvae as in experiment 1 but using only a larval density of 1 larva per $cm^2$.

Experiment 3 (pretreated ham mixed with wheat kernels): Wheat grains were rehydrated with 150% of their weight in distilled water for 48 h at room temperature and then sifted to separate the non-absorbed water. The ham residues pretreated at 35 °C for 24 h were mixed with the grains in a 1:2, 1:1, or 2:1 ratio for a total weight of 20 g. Such proportions were chosen as a preliminary evaluation to achieve the best rearing condition for the larvae. The mix was provided to the larvae in the same condition as in experiment 2.

Experiment 4 (pretreated ham mixed with smashed wheat kernels): Wheat grains were treated as in experiment 3, mechanically smashed with a meat tenderiser, and then mixed with ham as above. The mix was provided to the larvae as in experiment 3.

The weight of the larvae and the amount of substrate at the beginning and at the end of the experiments, as well as the number of live larvae at the end, were recorded. The final weights of the larvae and substrate were used as dependent variables, while the diet composition was the independent variable. Blackened larvae were considered to be prepupa.

#### 2.2.2. Statistical Analysis

The values of final larval and substrate weights were used as input for IBM SPSS Statistics software (version 29.0.1.0) to perform the homogeneity of variances analysis (Levene test, at a significance level of $p < 0.05$). After confirming the homogeneity of variances, we performed the parametric one-way ANOVA, followed by the Tukey post hoc test at a significance level of $p < 0.05$. Graphs were generated using OriginPro, Version 2025 (OriginLab Corporation, Northampton, MA, USA).

### *2.3. Integrated Refinery Process Design*

Within the present investigation, the authors propose an integrated approach involving a process design in which a bioreactor using *H. illucens* larvae treats selected food residue, such as fat-rich trimmings from the meat industry, which are largely and continuously available. An in-house black-box model was developed in Excel for process sizing: the model solves mass and energy balance around three main process steps, which are (i) bioconversion with *H. illucens*, (ii) anaerobic digestion (AD), and (iii) hydrothermal carbonisation (HTC). The model is capable of handling HTC process water stream recirculation, reaching convergence, thus providing a preliminary estimation of relevant energy and performance indicators. Relevant assumptions adopted by the model have been reported in Section 3.3. The process layout was developed based on the literature data and experimental insights to mitigate the inhibitory effects of lipid-rich substrates on downstream anaerobic digestion processes [37], thereby enhancing overall bioconversion efficiency.

## 3. Results and Discussion

### *3.1. Literature Review*

Many studies have investigated the potential of *H. illucens* (BSF) larvae to convert organic waste into valuable products such as animal feed, biofuels and fertilisers. To provide an overview of their application in energy production, a literature review was conducted on peer-reviewed articles published between January 2011 and January 2025. Searches were performed on the Scopus database using keywords such as "*Hermetia illucens*", "energy", and "biofuel". A total of 53 papers were initially retrieved; after excluding 2 book chapters, 2 conference proceedings, 4 reviews, and 25 articles not aligned with the scope of this study, 19 relevant articles were selected for analysis (Table 1). Table 1 summarises the key findings from the reviewed studies, which primarily focus on biodiesel production from BSF larvae [38–42]. In some cases, additional outputs such as biogas [39,42], protein feed, and bio-fertilisers [40,41] were also examined. The selected studies, spanning from 2011 to

2024, are mostly experimental and conducted at the laboratory scale. The majority originated from China, with further contributions from Malaysia, the United States, Denmark, and Egypt. Except for two studies [43,44], all research efforts explored the valorisation of residual biomasses—either individually or in combination—including manure, vegetable waste, and food scraps from kitchens and restaurants. While economic and environmental considerations are commonly introduced in the background sections of these articles, only three studies [45–47] included a quantitative environmental and economic assessment. Among these, climate change (measured via greenhouse gas emissions) was the most commonly analysed impact category. One study [47] adopted a broader life-cycle perspective, incorporating water depletion (WD), land use, and energy use (LU and EGU) into the assessment.

Several limitations emerged from the literature review:

- Limited scalability: Most studies remain at the lab scale, with few insights on pilot- or industrial-scale feasibility. Research on scale-up strategies—also accounting for regulatory constraints—is urgently needed.
- Geographical concentration: Research is geographically skewed, with a strong focus on China and Malaysia, while other regions remain under-represented. Expanding studies to these areas could yield new perspectives, especially in relation to local waste streams and legal frameworks.
- Economic viability: There is a lack of data on the cost effectiveness of larval biodiesel compared to conventional sources. More techno-economic analyses are required to assess its market competitiveness.
- Environmental assessments: Future work should include more comprehensive life-cycle assessments and compare BSF-based systems with conventional biofuel pathways across multiple impact categories and under realistic production scenarios.

Furthermore, the review revealed that the substrates used in the studies are often mixtures of poorly defined residuals, such as kitchen waste or manure, which are inherently variable and difficult to replicate. This lack of standardisation presents a barrier to designing scalable and reproducible bioconversion systems. To address this, it is critical to start from a substrate that is not only continuously available but also compositionally stable. Based on these findings, preliminary laboratory experiments were carried out to explore the suitability of a novel and underexplored substrate—cured meat residues—as a model feedstock. These materials were selected due to their consistent availability and limited alternative valorisation routes, making them a promising candidate for further investigations.

**Table 1.** Literature review results. CC: climate change; WD: water depletion; EGU: energy use; LU: land use.

| Authors | Year | Geographical Position | Methods | Substrate for Larval Growth | Main Products | Economic Aspects | Environmental Aspects |
|---|---|---|---|---|---|---|---|
| [47] | 2024 | No info | Theoretical | Residual biomass (rice straw + restaurant waste; dairy manure; restaurant waste) | biodiesel | x | CC, WD, EGU, and LU |
| [45] | 2024 | No info | Experimental (lab scale) | Protein-rich waste (bovine powder of MBM) | biodiesel | | CC |
| [48] | 2023 | China | Experimental (lab scale) | Kitchen waste | biodiesel | | |
| [44] | 2022 | No info | Experimental (lab scale) | No info | biodiesel blends | | |
| [49] | 2022 | Egypt | Experimental (lab scale) | Organic waste + microalgae + antioxidants | biodiesel | | |
| [50] | 2022 | No info | Experimental (lab scale) | Food waste | biodiesel from non-catalytic transesterification | | |
| [46] | 2021 | Denmark | Experimental (lab scale) | Fermented *Salicornia* sp. | biodiesel | x | CC |
| [51] | 2020 | Malaysia | Experimental (lab scale) | Perishable waste (fruits waste and food waste) | biodiesel | | |
| [52] | 2020 | China | Experimental (lab scale) | VFA from pig manure and rice straw | biodiesel | | |
| [43] | 2019 | Malaysia | Experimental (lab scale) | No info (commercial BSFL oil) | biodiesel | | |
| [53] | 2019 | No info | Experimental (lab scale) | Commercial chicken feed used to rear BSFs | biodiesel | | |
| [38] | 2018 | China | Experimental (lab scale) | Residues of corncob soaking with restaurant wastewater | larval grease and biogas | | |
| [42] | 2018 | USA | Experimental (lab scale) | Food waste | biomethane or biomethane + biodiesel | | |
| [41] | 2017 | China | Experimental (lab scale) | Corn stover + waste carrots | biodiesel + protein feed + bio-fertilisers | | |
| [40] | 2016 | USA | Experimental (lab scale) | Food wastes | biodiesel + animal feed | | |
| [39] | 2015 | China | Experimental (lab scale) | Biogas digestate from corncob and pig manure | biodiesel + biogas | | |
| [54] | 2012 | China | Experimental (lab scale) | Restaurant wastes | biodiesel | | |
| [55] | 2012 | China | Experimental (lab scale) | Restaurant wastes + rice straw | biodiesel | | |
| [56] | 2011 | China | Experimental (lab scale) | Organic waste (cattle manure, pig manure, and chicken manure) | biodiesel | | |

### 3.2. BSFL Rearing Experiments

In the first experiment, BSF larvae were submitted to a diet consisting of triturated, non-treated ham. Under these conditions, larval mortality reached 100%, regardless of density (1 or 5 larvae/$cm^2$). Within the first few days, larvae exhibited escape behaviour, abandoning the substrate and dying prematurely on the container walls. In the second experiment, after pretreating the ham, the larvae's acceptance of a ham-only diet improved. All larvae fed the control diet survived and reached the prepupal stage after 10 days. For the pretreated ham conditions, the survival rates were 38.75%, 51.25%, 81.25%, and 45% for pretreatment at 20 °C for 24 h, 20 °C for 48 h, 35 °C for 24 h, and 35 °C for 48 h, respectively (Table 2). There were statistically significant differences in the final larval weight across conditions (one-way ANOVA, $F_{4,19} = 109.236$, $p < 0.001$).

**Table 2.** Initial and final larval weights, final substrate weight, and number of live larvae for the pretreated ham condition. C refers to control conditions. H20-24 refers to the ham pretreated at 20 °C for 24 h. H20-48 refers to the ham pretreated at 20 °C for 48 h. H35-24 refers to the ham pretreated at 35 °C for 24 h. H35-48 refers to the ham pretreated at 35 °C for 48 h. The numbers 1 to 4 refer to the number of replicates. The initial weight of the larvae consists of the weights of 20 three-day-old larvae, and the final weight consists of the weights of the live larvae.

| Condition | Initial Weight of Larvae (g) | Final Number of Live Larvae | Final Weight of Live Larvae (g) | Final Weight of Substrate (g) |
|---|---|---|---|---|
| C1 | 0.0968 | 20 | 2.9229 | 2.3166 |
| C2 | 0.078 | 20 | 3.4237 | 2.5037 |
| C3 | 0.0732 | 20 | 2.7803 | 2.4666 |
| C4 | 0.0752 | 20 | 3.2834 | 2.0058 |
| H20-24-1 | 0.0826 | 4 | 0.1372 | 9.6217 |
| H20-24-2 | 0.104 | 4 | 0.0856 | 9.9723 |
| H20-24-3 | 0.0732 | 8 | 0.2015 | 9.8835 |
| H20-24-4 | 0.054 | 15 | 0.6921 | 11.2466 |
| H20-48-1 | 0.0852 | 4 | 0.1028 | 10.0014 |
| H20-48-2 | 0.0635 | 10 | 0.3313 | 12.0008 |
| H20-48-3 | 0.062 | 16 | 0.5708 | 11.3126 |
| H20-48-4 | 0.0787 | 11 | 0.3167 | 10.7964 |
| H35-24-1 | 0.0736 | 19 | 0.9801 | 11.3415 |
| H35-24-2 | 0.0697 | 14 | 0.7229 | 9.5901 |
| H35-24-3 | 0.0674 | 16 | 0.544 | 10.5957 |
| H35-24-4 | 0.0902 | 16 | 0.5881 | 11.3494 |
| H35-48-1 | 0.072 | 4 | 0.1366 | 9.9077 |
| H35-48-2 | 0.0803 | 11 | 0.4869 | 12.2903 |
| H35-48-3 | 0.0618 | 13 | 0.4579 | 10.581 |
| H35-48-4 | 0.0887 | 8 | 0.3295 | 12.0488 |

Larvae fed the control diet reached significantly higher final weights than those fed any ham-only diet (Figure 3). No significant differences in the final larval weight were observed between the different pretreatment conditions, and none of the larvae fed with ham reached the prepupal stage within the 10-day period. Furthermore, substrate consumption was minimal in all ham treatments, with only the control condition exhibiting a significant reduction in substrate mass (one-way ANOVA, $F_{4,19} = 87.631$, $p < 0.001$).

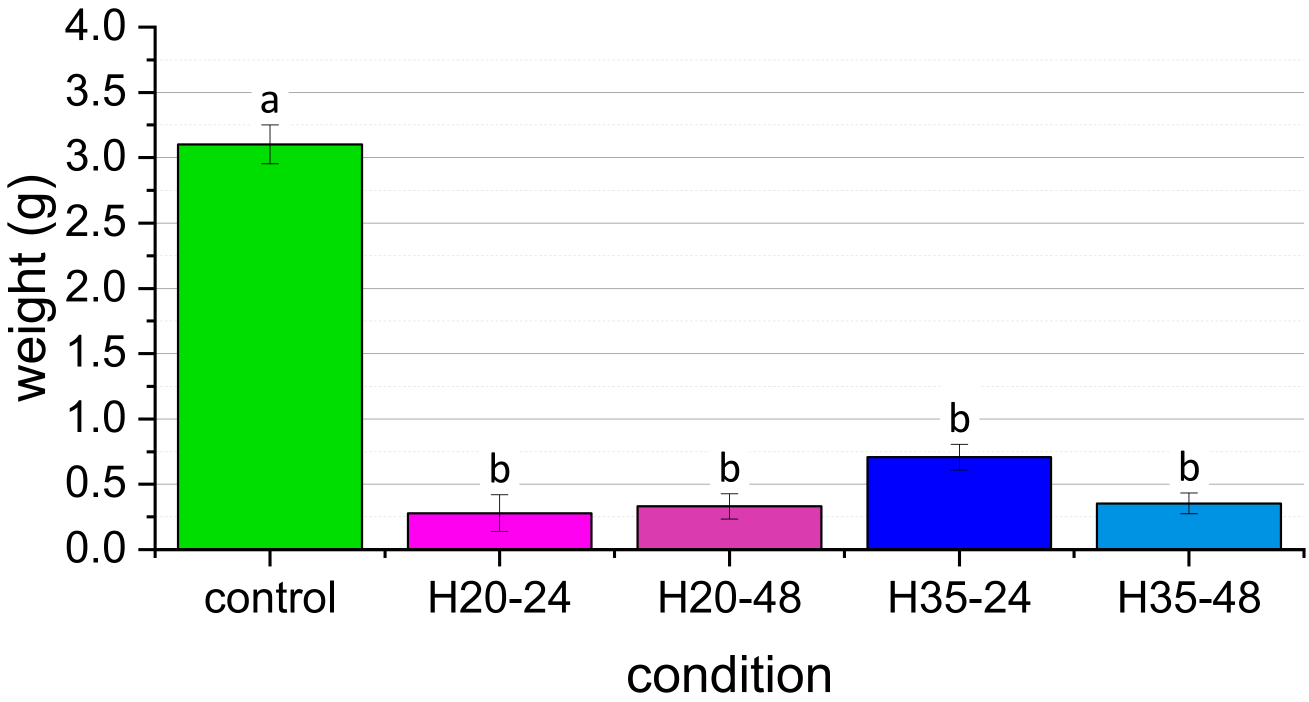


**Figure 3.** Final weights of larvae fed with different conditions of pretreated ham. The bars represent the mean value of the weight ± SD. The green bar represents the control condition. The pink-toned bars represent the ham pretreated at 20 °C for 24 (H20-24) or 48 h (H20-48), and the blue-toned bars represent the ham pretreated at 35 °C for 24 (H35-24) or 48 h (H35-48). The letters represent statistical results from the one-way ANOVA with Tukey's post hoc test ($p < 0.05$). Different letters mean significant differences between conditions, while the same letters mean no significant differences.

Given that the highest survival rate was achieved with ham pretreated at 35 °C for 24 h, subsequent experiments were conducted under this condition. In experiment 3, rehydrated whole-wheat grains were mixed with pretreated ham and fed to BSF larvae, using various ham-to-wheat ratios. Larval survival was 96.5% for the 1:2 ham-to-wheat proportion and 95% for both the 1:1 and 2:1 proportions, while all larvae in the control diet again reached the prepupal stage after 10 days. (Table 3). A significant difference in the final larval weight was observed between conditions (one-way ANOVA, $F_{3,15} = 22.558$, $p < 0.001$). Control-fed larvae attained significantly higher weights than larvae in all other conditions, and larvae in the 1:2 mixture condition had significantly higher weights than those in the 2:1 mixture (Figure 4). None of the larvae fed with the mixtures reached the prepupal stage after 10 days, and a considerable amount of substrate remained unconsumed in all mixture conditions. This is expected, as larvae can only digest the inner portion of whole-wheat grains, leaving the outer husk intact. However, there were no significant differences in residual substrate weight across the various ham–wheat mixtures (Table 3), with only the control group showing a significantly greater reduction in the substrate mass (one-way ANOVA, $F_{3,15} = 74.888$, $p < 0.001$).

To improve larval access to the nutrients within the wheat grains, experiment 4 employed mechanically macerated wheat. With this modification, survival rates were 96.25% for the 1:2 ham-to-wheat ratio, 92.5% for the 1:1 ratio, and 81.5% for the 2:1 ratio (Table 4). Statistically significant differences in final larval weight were again detected (one-way ANOVA, $F_{3,15} = 14.464$, $p < 0.001$). Larvae fed the control and 1:2 mixture diets had comparable weights, both significantly higher than those fed the 1:1 or 2:1 mixture (Figure 5). Additionally, the 1:2 condition showed significantly greater substrate reduction compared to the 2:1 mixture. Substrate consumption in the 1:1 condition did not differ significantly from that in the 1:2 and 2:1 conditions. Overall, the control condition consistently exhibited the greatest substrate consumption (one-way ANOVA, $F_{3,15} = 73.660$, $p < 0.001$).

**Table 3.** Initial and final larval weights, final substrate weight, and number of live larvae for the pretreated ham mixture with whole-wheat conditions. C refers to control conditions. H:Ww refers to the mixture of ham pretreated at 35 °C for 24 h and the whole rehydrated wheat. The proportions of ham and wheat are represented by −1:2, −1:1, and −2:1. The numbers 1 to 4 refer to the number of replicates. The initial weight of the larvae consists of the weights of 20 three-day-old larvae, and the final weight consists of the weights of the live larvae.

| Condition | Initial Weight of Larvae (g) | Final Number of Live Larvae | Final Weight of Live Larvae (g) | Final Weight of Substrate (g) |
|---|---|---|---|---|
| C1 | 0.0326 | 20 | 3.7909 | 2.8482 |
| C2 | 0.0312 | 20 | 3.9045 | 3.2135 |
| C3 | 0.0269 | 20 | 3.9149 | 5.1445 |
| C4 | 0.0299 | 20 | 3.7564 | 3.2185 |
| H:Ww - 1:2-1 | 0.0339 | 20 | 2.7292 | 9.784 |
| H:Ww - 1:2-2 | 0.0271 | 20 | 3.0678 | 10.2723 |
| H:Ww - 1:2-3 | 0.03 | 20 | 2.4968 | 10.0944 |
| H:Ww - 1:2-4 | 0.0289 | 17 | 3.1838 | 11.3387 |
| H:Ww - 1:1-1 | 0.022 | 20 | 2.056 | 12.265 |
| H:Ww - 1:1-2 | 0.0331 | 18 | 1.995 | 10.2389 |
| H:Ww - 1:1-3 | 0.0268 | 20 | 2.8283 | 10.0753 |
| H:Ww - 1:1-4 | 0.0337 | 18 | 1.0433 | 10.9851 |
| H:Ww - 2:1-1 | 0.0311 | 20 | 1.6396 | 12.2697 |
| H:Ww - 2:1-2 | 0.0297 | 20 | 1.1315 | 11.3488 |
| H:Ww - 2:1-3 | 0.0313 | 17 | 1.2129 | 11.0729 |
| H:Ww - 2:1-4 | 0.0281 | 19 | 1.8984 | 10.9928 |

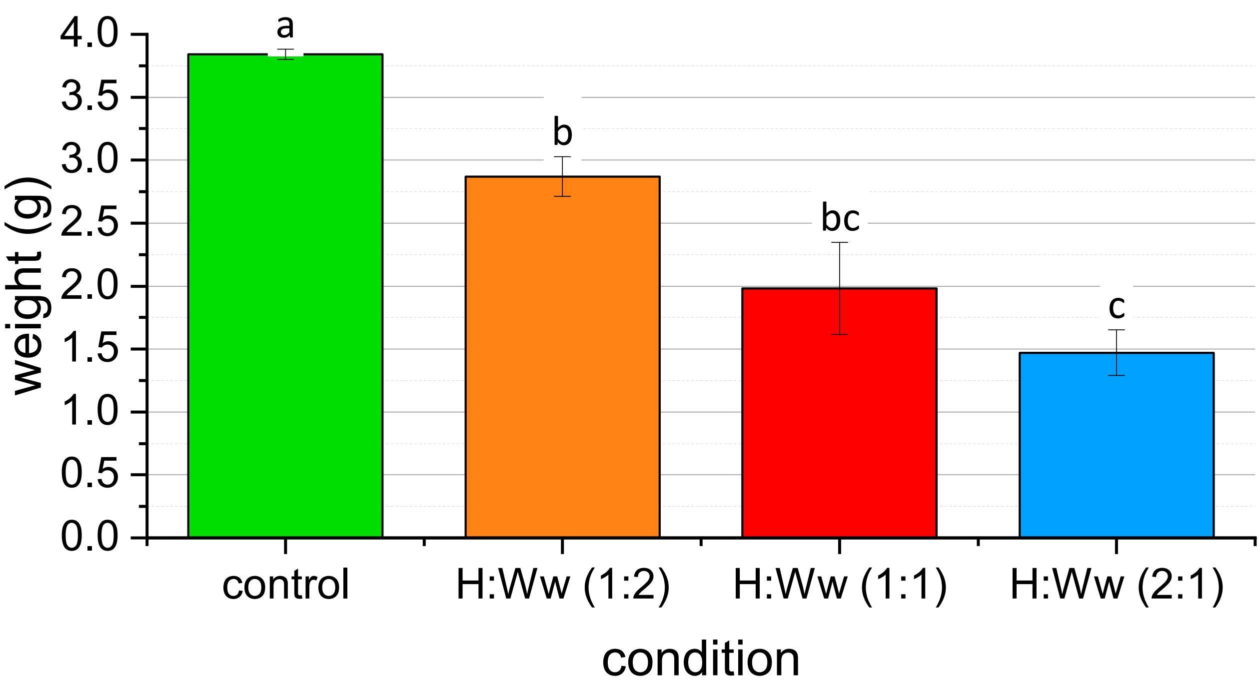


**Figure 4.** Final weights of larvae fed with different conditions of pretreated ham and whole-wheat grains (H:Ww). The bars represent the mean value of the weight ± SD. The green bar represents the control condition. The orange bar represents the mixture in the proportion 1:2 of ham and wheat. The red bar represents the mixture in the proportion 1:1, and the blue bar in the proportion 2:1. The letters represent statistical results from the one-way ANOVA with Tukey's post hoc test ($p < 0.05$). Different letters mean significant differences between conditions, while the same letters mean no significant differences.

**Table 4.** Initial and final larval weights, final substrate weight, and number of live larvae for the pretreated ham mixture with macerated wheat conditions. C refers to control conditions. H:Wm refers to the mixture of ham pretreated at 35 °C for 24 h and the macerated, rehydrated wheat. The proportions of ham and wheat are represented by −1:2, −1:1, and −2:1. The numbers 1 to 4 refer to the number of replicates. The initial weight of the larvae consists of the weights of 20 three-day-old larvae, and the final weight consists of the weights of the live larvae.

| Condition | Initial Weight of Larvae (g) | Final Number of Live Larvae | Final Weight of Live Larvae (g) | Final Weight of Substrate (g) |
|---|---|---|---|---|
| C1 | 0.038 | 20 | 3.435 | 4.1136 |
| C2 | 0.0396 | 20 | 2.6019 | 2.5495 |
| C3 | 0.0395 | 20 | 3.4191 | 3.0033 |
| C4 | 0.037 | 20 | 3.2873 | 2.4235 |
| H:Wm - 1:2-1 | 0.04 | 19 | 3.7746 | 8.7996 |
| H:Wm - 1:2-2 | 0.0412 | 20 | 2.9228 | 7.8382 |
| H:Wm - 1:2-3 | 0.037 | 19 | 2.9918 | 9.6619 |
| H:Wm - 1:2-4 | 0.0474 | 19 | 2.3569 | 8.3898 |
| H:Wm - 1:1-1 | 0.0541 | 19 | 1.3304 | 9.6389 |
| H:Wm - 1:1-2 | 0.045 | 20 | 2.5733 | 8.7385 |
| H:Wm - 1:1-3 | 0.0436 | 17 | 2.3186 | 9.34 |
| H:Wm - 1:1-4 | 0.0468 | 18 | 2.188 | 8.5014 |
| H:Wm - 2:1-1 | 0.0407 | 18 | 1.7308 | 10.7884 |
| H:Wm - 2:1-2 | 0.0422 | 16 | 0.7182 | 10.6487 |
| H:Wm - 2:1-3 | 0.0454 | 18 | 1.0626 | 11.089 |
| H:Wm - 2:1-4 | 0.0337 | 13 | 1.1283 | 9.0354 |

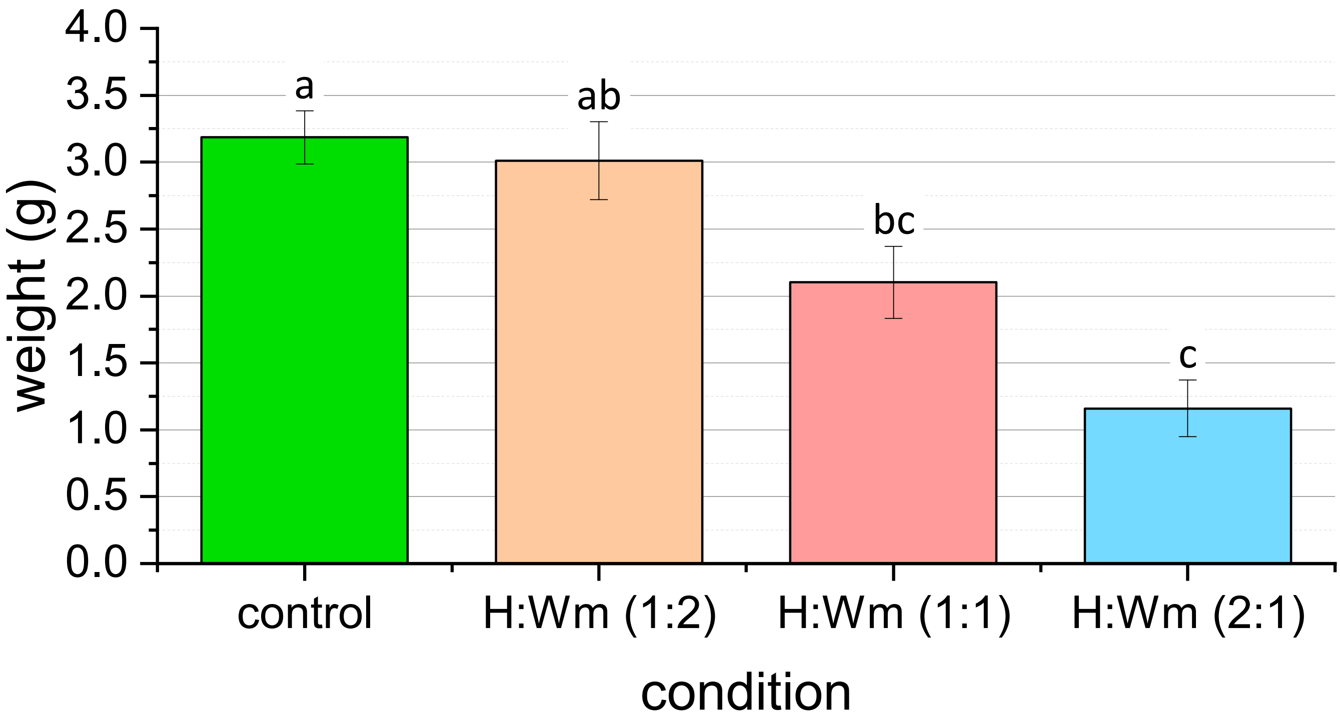


**Figure 5.** Final weights of larvae fed with different conditions of pretreated ham and macerated wheat grains (H:Wm). The bars represent the mean value of the weight ± SD. The green bar represents the control condition. The light orange bar represents the mixture in a proportion of 1:2 of ham and wheat. The light red bar represents the mixture in the proportion 1:1 and the light blue bar in the proportion 2:1. The letters represent statistical results from the one-way ANOVA with Tukey's post hoc test ($p < 0.05$). Different letters mean significant differences between conditions, while the same letters mean no significant differences.

These experiments demonstrate the challenges associated with using ham industry residues for bioconversion with *H. illucens*. Without any pretreatment, ham was rejected by the larvae, likely due to high fat and salt contents, which cause rapid dehydration and stiffening of the substrate, making it unsuitable for larval feeding. Efforts to counter this by adding water were ineffective; instead of increasing moisture availability, this created a viscous fat–water emulsion that either repelled the larvae or caused them to become trapped, leading to mortality. Previous studies shown that a salt concentration as low as 2% negatively impacts BSFL development, with levels above 4% severely limiting growth and survival [57]. Ham residues typically exceed this salt threshold.

To increase the acceptance and reduce the mortality of *H. illucens* larvae on a ham-only diet, the ham residues were pretreated to reduce the salinity and improve their tenderisation. Even though their survival improved with the pretreatment of the ham, the weight gain by the larvae was limited. Some other studies also observed reduced body weights and survival of the larvae when exposed to excess protein or fat in their diet. Experiments performed by Kawasaki et al. [58] suggest that the percentage of meat should be less than 50% of dry matter.

To better balance the nutrient composition, pretreated ham was mixed with wheat grains. The wheat was chosen due to its constant availability throughout the year. Also, wheat grains can be infected by phytopathogenic fungi, causing diseases like Fusarium Head Blight (FHB). The infection results in the presence of trichothecene mycotoxins in the grains, which are highly toxic to humans and livestock but do not interfere in the *H. illucens* development [59–61]. Despite these efforts, challenges persist. Substrate drying and stiffening over time, particularly due to moisture transfer between ham and wheat, limited the effectiveness of the mixtures. Nevertheless, the maceration of wheat improved nutrient accessibility, and the 1:2 ham-to-wheat mixture emerged as the best-performing condition among all tested. Although larvae did not reach the prepupal stage, they achieved weight gains equivalent to those observed in the control group.

In conclusion, effective bioconversion of ham residues by *H. illucens* requires both pretreatment and dietary supplementation. The best outcomes were obtained when ham constituted the smallest component of the substrate. While adding vegetables could provide a more natural and accessible alternative to wheat, such diets could influence larval body composition, particularly lipid content, and affect the energy efficiency of the process. Therefore, substrate selection should consider not only larval acceptance and survival but also the final biomass's nutritional composition and energy output.

### *3.3. Integrated Process Design*

The experimental larval pretreatment described in the previous section is intended as a part of a broader biorefinery system aimed at producing bioenergy, the design of which is outlined below. According to the European Biogas Association (EBA), European biogas and biomethane production reached a combined total of 22 billion cubic meters in 2023 [62]. The REPowerEU Plan targets an increase in this production to 35 billion cubic meters per year by 2030, supporting efforts to reduce Europe's reliance on foreign fossil fuels and mitigate consumers' exposure to volatile natural gas prices [63]. Anaerobic digestion (AD) represents a suitable solution to treat biodegradable materials, such as food waste and residues, primarily due to their high volatile solids (VS) content relative to total solids (TS) [62]. Moreover, food waste and residues offer a higher biochemical methane potential (BMP) for AD compared to other substrates, such as animal manure and sewage sludge [37,64].

Several studies highlight the benefits of integrating AD with hydrothermal processes, particularly hydrothermal carbonisation (HTC). The integration strategy mainly consists in feeding the hydrothermal treatment unit with solid digestate [65–67]; this approach has been shown to improve overall energy recovery, enhance the fuel properties of the resulting hydrochar, and facilitate better dewaterability of the digestate after HTC [67].

HTC also produces process water containing a significant amount of organic compounds, making it a potential valuable input for AD units [64]. The anaerobic digestion of the HTC process water has been investigated by Wirth and Mumme [68] and by Medina-Martos et al. [69], whereas Wang and Lee and Kassim et al. describe an integrated approach envisaging HTC process water recirculation back to the AD unit [67,70]. Despite these benefits, recirculating HTC process water can present challenges due to its typically high level of acidity, with pH values between 2.7 and 3.4, depending on the feedstock used [71,72]. Therefore, careful pH monitoring and correction are essential to prevent potential inhibition of methane production in the anaerobic digester [73].

Within the present investigation, we propose an integrated biorefinery approach that includes a bioreactor treating selected food residues (e.g., meat industry trimming residues and ham residues) using *H. illucens*. The desired impact of this process unit is expected to consist in a mitigation of the detrimental effects of fat-rich substrates on anaerobic digestion [37]. The integrated system, illustrated in Figure 6, has led to the process design and consists in the following:

1. Three main process units: these are bioconversion with *H. illucens*, anaerobic digestion (AD), and hydrothermal carbonisation (HTC);
2. Thermally self-sustainable process: the system is designed to be thermally self-sufficient through the partial use of the produced hydrochar as a fuel in boiler B-01; this boiler provides heat to both the HTC process and the anaerobic digestion unit;
3. Thermal integration strategies for HTC: to reduce energy consumption, water is employed as a heat transfer medium for HTC feed preheating (via heat exchanger E-01) and for cooling the HTC product (via E-02);
4. Heat recovery to support anaerobic digestion: waste heat recovered from the HTC process using exchanger E-03 is utilised to partially meet the thermal energy demand of the anaerobic digestion reactor R-02.

Overall, the process enables the recovery of several valuable outputs, including biogas (stream n. 4), hydrochar (stream "Char to Storage"), ashes from boiler B-01, and purge water. The off-gas production from HTC is considered negligible. While various technologies are available for biogas upgrading [74,75], membrane-based $CO_2$ separation is assumed in this study for estimating the system's energy requirements.

The performance assessment of the proposed system is based on the assumptions summarised in Tables 5 and 6. Specifically:

- The composition of stream n. 1 (feedstock) is taken from Eisert's report [76];
- The specific electricity consumptions for the biogas upgrading unit are taken from Lombardi and Francini [77];
- The specific heat capacity of the solid fraction entering the HTC reactor is based on data reported by Arlabosse et al. [78];
- The high heating value (HHV) of the hydrochar, on a dry basis, is assumed to be 12 MJ/kg; this value aligns with the findings of Cao [79], who consider digestates from AD as feedstock for the HTC process;
- The heat of reaction for the HTC process is considered negligible;
- The equivalent electrical energy consumption of heat rejection is estimated at 2% of the removed thermal duty.

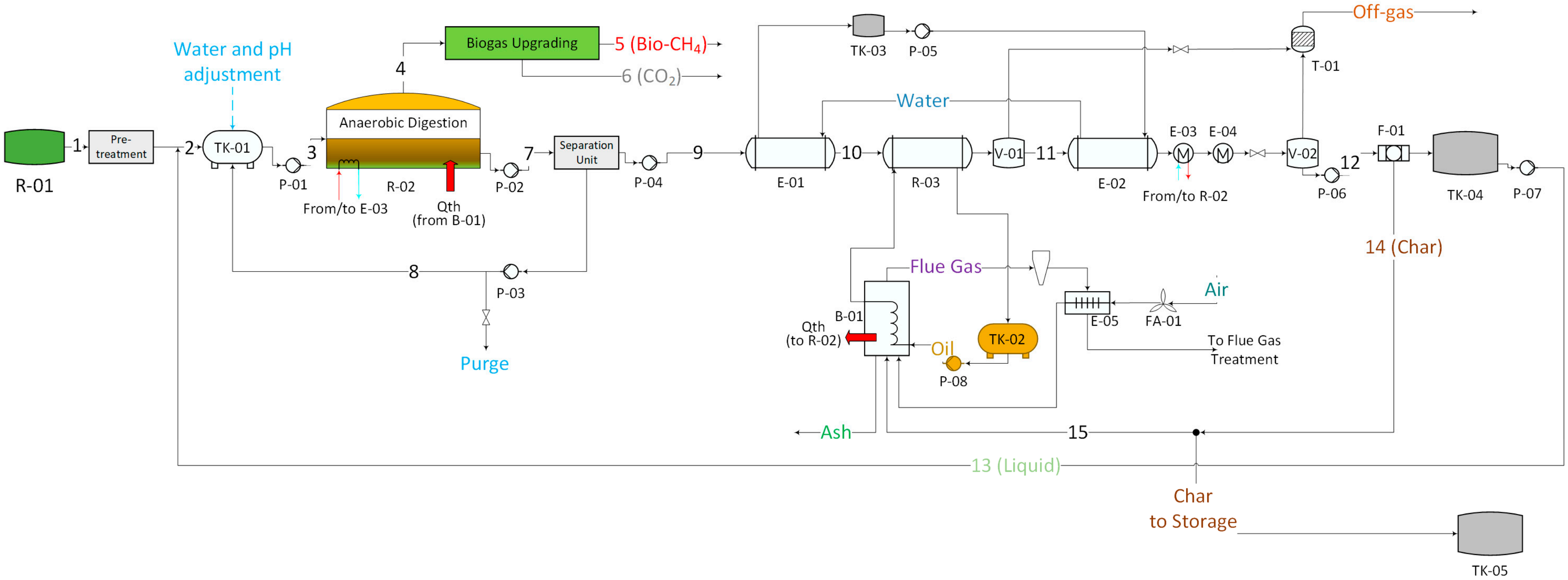


**Figure 6.** Integrated process featuring biodigestor + anaerobic digestor + HTC.

**Table 5.** Main assumptions on composition of the relevant streams considered for the proposed process. The specific indicators refer to the feedstock (e.g., stream n. 1 from Figure 6) or other relevant streams. TS = total solids; VS = volatile solids.

| **Main Assumptions—Compositions of Relevant Streams** | | |
|---|---|---|
| | Stream n.1: feedstock | |
| TS | 39% | %w |
| VS | 37% | %w |
| Ash | 2% | %w |
| Water | 61% | %w |
| | Stream n.3: AD inlet | |
| Water | 86% | %w |
| TS | 14% | %w |
| | Stream n.4: Biogas | |
| $CO_2$ | 36% | %vol |
| $CH_4$ | 54% | %vol |
| Water | 10% | %vol |
| | Stream n.8: water from separation unit | |
| Water | 100% | %w |
| | Stream n.9: HTC input | |
| Water | 75% | %w |
| TS | 25% | %w |
| | Stream n.13: liquid from F-01 | |
| Water | 94% | %w |
| TS | 6% | %w |
| | Stream n.14: char from F-01 | |
| Water | 40% | %w |
| TS | 60% | %w |

**Table 6.** Main assumptions on performance indicators and process parameters. The specific indicators refer to the feedstock (e.g., stream n. 1 from Figure 6) or other relevant streams. TS = total solids; VS = volatile solids.

| **Main Assumptions—Performance Indicators and Process Parameters** | | | |
|---|---|---|---|
| Process unit | Assumption | Value | Unit |
| R-02 (AD—anaerobic digestor) | Digestate mass yield | 94% | %w - kg(7)/kg(3) |
| | Qlosses (%Qadiabatic) | 92% | %adiabatic duty |
| | cp_AD inlet | 3.847 | kJ/kg/K |
| | AD impeller | 13.760 | kJe/kg(1) |
| | Biogas upgrading | 94.319 | kJe/kg(1) |
| HTC (E-01 + R-03 + E-02) | T9 | 55 | °C |
| | T10 | 110 | °C |
| | T11 | 210 | °C |
| | T_E-02_out | 139 | °C |
| | cp_solid fraction stream n.9 | 1.763 | kJ/kg/K |
| | cp_sludges_HTC | 3.580 | kJ/kg/K |
| Thermal integration: water E03-R-02 | T_water to E-03 | 60 | °C |
| | T_water from E-03 | 75 | °C |
| Boiler | η_boiler | 80% | |
| | HHV | 12 | MJ/kg_dry fuel |
| | LHV | 6.32 | MJ/kg(15) |
| | cp_Flue gas | 1.300 | kJ/kg/K |
| | cp_Ash | 0.840 | kJ/kg/K |
| | cp_Air | 1.025 | kJ/kg/K |
| | Air-to-fuel ratio | 7 | *w*/*w* |
| | Specific electric consumption | 288 | kJ/kg(15) |
| | ρ_Oil | 700 | $kg/m^3$ |
| | cp_Oil | 2.51 | kJ/kg/K |

Considering the reported assumptions, the proposed process's most relevant mass flow rates and energy balance are reported in Table 7. The preliminary performance evaluation indicates that approximately 0.06 kg of biomethane is produced per kilogram of feedstock (i.e., stream n.1 consisting of *H. illucens* larvae). Almost 160 kJe is required by the process per kilogram of feedstock, most of which (approximately 68%) is needed to support the anaerobic digestion, particularly due to the high electric consumption associated with the biogas upgrading unit.

The estimated biomethane potential based on the process design is approximately 226 L/kgVS. In addition, the process produces 0.257 kg of hydrochar per kg(1) of feedstock, which can be further valorised, for instance, as a soil amendment.

The conceptual design illustrated here will be further validated and refined through future experimental activities mainly focusing on feedstock characterisation and biomethane potential assessment, as well as the development of more detailed process models. The current calculations rely on the assumption of the larval-based feedstock composition taken from the literature (see Table 5), which needs to be further investigated for a more accurate estimation of the performance of the AD unit. The latter will significantly affect relevant performance indicators, such as the biomethane potential.

**Table 7.** Heat and mass balance of the integrated process combining a bioreactor, anaerobic digestor, and HTC. Specific indicators are referred to the feedstock (stream n.1 from Figure 6).

| Mass Balance | | | |
|---|---|---|---|
| Stream # | Description | Value | Unit |
| 1 | Feedstock | 1.000 | kg/kg(1) |
| 3 | AD input | 3.056 | kg/kg(1) |
| 5 | Bio-$CH_4$ | 0.060 | kg/kg(1) |
| 9 | HTC input | 1.028 | kg/kg(1) |
| 13 | HTC liquid to AD | 0.666 | kg/kg(1) |
| 14 | Hydrochar | 0.362 | kg/kg(1) |
| 15 | Hydrochar to B-01 | 0.105 | kg/kg(1) |
| Ash | Ashes from B-01 | 0.003 | kg/kg(1) |
| Purge | Excess water from separation unit | 0.455 | kg/kg(1) |
| **Energy Balance** | | | |
| Unit | Description | Value | Unit |
| AD | Pumps (P-01, P-02, and P-03) | 0.90 | kJe/kg(1) |
| | AD impeller | 13.76 | kJe/kg(1) |
| | Biogas upgrading | 94.32 | kJe/kg(1) |
| | Thermal duty (Qth) | 20.35 | kJth/kg(1) |
| HTC | Pumps (P-04, P-05, P-06, and P-07) | 10.77 | kJe/kg(1) |
| | Heat removal and integration, electric equivalent | 4.56 | kJe/kg(1) |
| B-01 | Auxiliaries (pump and fan) | 35.29 | kJe/kg(1) |
| | Boiler duty B-01 | 485.59 | kJth/kg(1) |

Moreover, comprehensive techno-economic analyses [75,80,81] are needed to estimate the levelised cost of biomethane production and the required process scale up suitable for industrial applications.

Despite the promising potential highlighted, regulatory barriers remain critical, particularly concerning larvae use. Currently, the rearing of larvae on animal-based residual substrates is not permitted, even for energy purposes. As in other sectors [82], it becomes evident that implementing circular economy models faces significant regulatory constraints and a lack of tailored economic incentives. It is, therefore, essential to investigate collaborative governance models that engage both local and global stakeholders in order to develop more flexible policies that foster circularity across all sectors. Furthermore, exploring appropriate economic incentives could support the adoption and wider diffusion of circular practices.

## 4. Conclusions

This study investigated the feasibility and limitations of developing an integrated biorefinery system for bioenergy production from widely available, yet underutilised, residual materials, specifically, ham processing residues. The proposed system integrates larval digestion (using *Hermetia illucens*), anaerobic digestion (AD), and hydrothermal carbonisation (HTC) to optimise energy recovery and material valorisation. A comprehensive literature review highlighted that larvae have primarily been applied for energy production using mixed and non-replicable substrates, with a prevailing focus on fat extraction for biofuel conversion. In contrast, this study explores the novel role of larvae as a biological pretreatment step for fat-rich residues prior to AD and HTC, aiming to mitigate the inhibitory effects of lipids in anaerobic systems. Experimental results confirmed that ham processing residues cannot be used in their raw form due to unfavourable properties; instead, they require pretreatment and mixing with cereal residues to become suitable feedstock. Nonetheless, the composition of these residues allows for the definition of optimal processing conditions, supporting system feasibility. The theoretical performance of the integrated process yields approximately 226 L of biomethane per kg of volatile solids (VS) and 0.257 kg of hydrochar per kg of residue, the latter with potential applications such as soil amendment. Further experimental activity is required to assess and validate process performance: the composition of the larvae-based feedstock fed with ham residues is required, estimating the proximal analysis and protein/lipid/carbohydrate content, affecting the anaerobic digestion performance together with the most relevant specific indicators. Nevertheless, the outcomes underscore the potential of a synergistic biorefinery model to enhance energy recovery, reduce waste, and enable circular resources utilisation.

Although experimental data have been collected within the present investigation, providing a perspective of the feedstock production (i.e., pretreatment step consisting in ham residues processing with larvae), a more extensive testing of the proposed technology is necessary to optimise the process. However, the here-proposed conceptual design shows valuable insights illustrating a new role of larval digestion pretreatment combined with anaerobic digestion and hydrothermal processes. The study underlines potential challenges of the new technology, leaving room for future research to design more accurate process models to support towards optimising performance and environmental and economic assessments.

Future research will address these gaps, leveraging a thorough economic analysis to investigate system scalability for relevant industrial applications.

Despite the demonstrated potential, regulatory constraints currently hinder the adoption of larval pretreatment, as existing legislation does not permit its use in waste management and energy production. In addition to restricting current applications, regulatory barriers prevent the upscaling of these systems, thereby constraining a comprehensive evaluation of the potential environmental, economic, and technological benefits they could offer at a larger scale. These bottlenecks reflect the broader issue of regulatory frameworks lagging scientific innovation and emerging biotechnologies. To support the advancement of circular economy strategies, regulatory systems must be continuously revised and aligned with the latest scientific evidence and technological progress. By modernising policy to accommodate innovative practices such as larval pretreatment, society can unlock new opportunities in waste valorisation, bioenergy production, and sustainable resource management.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| Abbreviation | Meaning |
|---|---|
| AD | Anaerobic digestion |
| HTC | Hydrothermal carbonization |
| IEA | International Energy Agency |
| SDS | Sustainable Development Scenario |
| VS | Volatile solids |
| TS | Total solids |
| BSF | Black Soldier Fly (*Hermetia illucens*) |
| BSF | Black Soldier Fly larvae (*Hermetia illucens*) |
| RH | Relative humidity |
| IPIFF | International Platform of Insects for Food and Feed |
| ABP | Animal By-Products |
| WD | Water depletion |
| LU | Land use |
| EGU | Energy use |
| EBA | European Biogas Association |
| EU | European Union |
| FHB | Fusarium Head Blight |
| REPowerEU | European energy plan aiming to reduce dependence on fossil fuels |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| FW | Food waste |
| BMP | Biochemical methane potential |
| R&D | Research and development |
| B-01 | Boiler unit (used in the integrated system) |
| E-01, E-02, E-03 | Heat exchangers (used in HTC and AD thermal integration) |
| R-02 | Anaerobic digestion reactor |

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