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Recovery of Fruit and Vegetable Waste from Large-Scale Retail Through *Hermetia illucens* L. Bioconversion: A Life Cycle Assessment Approach

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Featured Application

The findings of this study are directly applicable to the design of sustainable insect-based bioconversion facilities that process fruit and vegetable waste from large-scale retail. The study demonstrated that, when a conditioning additive is used, its choice is a primary driver of the carbon footprint of black soldier fly larvae production. This work provides actionable guidance for facility operators and value chain designers. The results of the present study support the development of circular bioeconomy strategies in which retail food waste is upcycled into high-value animal protein ingredients, contributing to reduced dependence on conventional feed sources such as soybean meal, and to the achievement of EU food waste reduction targets under the Farm to Fork Strategy.

Abstract

Fruit and vegetable waste (FVW) from large-scale retail is an abundant, relatively homogeneous feedstock for black soldier fly (*Hermetia illucens*) larvae, an alternative to composting. This study assessed, by life cycle assessment (LCA), the environmental performance of a pilot plant producing 15-day-old larvae as animal protein and tested whether the additive conditioning of the FVW changes that performance. Three substrates were compared (FVW with 20% bakery waste, 20% bran, and 2% sawdust, respectively) using climate change (GWP100a, IPCC 2007), economic allocation, Monte Carlo simulation, and transport distance sensitivity. The scenario ranking depended on the functional unit: per Mg of waste, the sawdust substrate was lowest (39.75 kg CO_2eq), whereas, per kg of protein, the bran substrate was best (8.87 kg CO_2eq, ~66% below bakery waste). Electricity, additive, and starter diet dominated the footprint. The conditioning additive, not the waste itself, governed sustainability; the bran–bakery waste difference was statistically discernible.

Keywords: black soldier fly larvae; insect-based feed; food waste valorization; circular bioeconomy; global warming potential; substrate conditioning; frass

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1. Introduction

Food loss and waste represent a global environmental challenge, with around 1.3 billion tons generated annually along the supply chain [1]. The 2030 Agenda Target 12.3 aims to reduce food waste and losses, as unmanaged disposal contributes to methane emissions and climate change [2]. Therefore, valorizing organic waste as a secondary raw material is both a waste management and climate strategy. Agri-food waste, dominated by carbohydrates, proteins, and lipids, can be recovered [3] biologically or thermochemically into energy or value-added chemicals, via routes ranging from anaerobic digestion to incineration and pyrolysis [4]. Composting, the most common biological option, is slow and its emissions dominate the footprint of organic waste management [5].

Against this background, insect-mediated bioconversion has emerged as an alternative that turns the same waste into animal biomass while emitting less.

The black soldier fly (BSF) (*Hermetia illucens* L., Diptera: *Stratiomyidae*) is among the most studied insects for this purpose. Using fly larvae to process organic waste is an idea over a century old [6], and *H. illucens* larvae are of particular interest for consuming a wide range of substrates efficiently and safely [7,8]. Compared with composting, BSF larvae (BSFL) reduce organic waste faster, in larger volumes, and with lower and shorter emissions [9–11], cutting greenhouse gas emissions by over 90% for some feedstocks [12]. The larval biomass can be valorized into feed, energy, and green chemistry products depending on substrate, technology, and demand.

1.1. Food Waste at Retail

In the European Union, food waste reached about 58 million tonnes of fresh mass in 2023, unevenly distributed across the supply chain (Table 1), with households being the main source of food waste, which is defined by EU legislation as waste generated along the food supply chain from production to consumption [13,14].

Although a modest share of the total, retail waste is an attractive entry point for recovery: it is more homogeneous than household or catering waste [15], and it is dominated by fruit and vegetables, 60–70% of the discarded weight [16], arising mainly from non-conformity, overstocking, and damaged packaging [17]. Since EU rules exclude waste containing meat, fish, or catering residues from insect feed (Section 1.2), retail fruit and vegetable waste (FVW) is well suited to BSFL rearing.

Table 1. Amounts of food waste at EU level (source: [18]).

Sectors	Fresh Mass		
	Tg y-1	%	Kg Inhabitant y-1
Households	30.9	53.0	69
Manufacture of food products and beverages	10.8	18.5	24
Restaurants and food services	6.5	11.1	12
Primary production	5.6	9.6	14
Retail and other distribution of food	4.5	7.7	10
Total food waste 2	58.3	100	129

1.2. Biology and Life Cycle of the Black Soldier Fly and European Regulatory Framework

H. illucens is a non-pest fly native to the warm regions of the Americas and now widespread across temperate and tropical zones [19,20]. Its life cycle comprises four stages, egg, larva, pupa, and adult, with eggs hatching within 4–14 days depending on temperature [21] and larvae passing through five to seven instars to reach maturity in 15–20 days. Larvae efficiently convert residual biomass owing to their polyphagous feeding

behavior and specialized digestive system [19,20,22]. The mature prepupa stops feeding, darkens, and migrates to pupate at a dry site [23,24]; adults then emerge after 10–14 days and mate, each female laying about 900 eggs on average [21]; they do not feed, are weak fliers, and do not approach humans or animals [25,26].

Demand for farmed insects is rising as the industry seeks feed ingredients with a lower environmental footprint than soybean meal or fishmeal, prompting an intensive update of the European legislative framework. Insect production in the EU is regulated for safety by Regulation (EC) 183/2005 [27], which sets hygiene standards for animal feed, and by the Regulation on animal by-products [28], which includes farmed insects among "farmed animals." FVWs qualify as foodstuffs not intended for human consumption due to commercial reasons or production or packaging defects [29]. Being free from animal by-products, they comply with Regulation [28]'s prohibition on feeding farmed animals with animal by-products and derived products, including catering waste or feed materials containing or derived from catering waste. Therefore, insects intended for feed may only be reared on substrates of non-animal origin, excluding waste containing meat, fish, or catering residues [30], even though such substrates have been shown to be technically suitable for bioconversion. By contrast, ref. [31] authorized seven insect species, including *H. illucens*, as processed animal protein (PAP) for aquaculture feed; Ref. [32] later set requirements for imports from third countries, while ref. [33] extended insect PAP to poultry, pig, aquaculture, and pet food diets.

1.3. Substrate Effect and Product Valorization

The composition and yield of BSFL depend strongly on the rearing substrate, tested across municipal and market waste, agro-industrial by-products, and manure [34,35], as well as feed mill residues, mushrooms, okara, and sewage sludge [24,36]. The substrate governs larval development, survival, waste reduction efficiency, and the nutritional profile [37,38], and rearing requires control of substrate moisture, larval density, feeding rate, and temperature [34,39,40]. Larval biomass yields several marketable products [35,41]. Dried larvae contain about 30–40% protein and 20–40% lipid [20,34], with a complete essential amino acid profile, supporting their use as a partial soybean meal or fishmeal replacement in poultry, fish, swine, and pet diets [42,43]. The lauric acid-rich lipid suits biodiesel and personal care products [35,44], while chitin and haemolymph peptides with antimicrobial activity find use in materials, cosmetics, and biomedicine [45,46]. Frass, the residue left after larval separation, can be a nutrient-rich organic fertilizer.

1.4. Aim and Novelty of the Study

Most BSFL life cycle assessments compare feedstocks, so the contribution of the conditioning additive is rarely isolated, yet for a wet feedstock, such as FVW, it is a design choice with its own environmental cost and effect on larval yield. Within the Italian HERMES project, three conditioning substrates and a semi-automated rearing-and-separation prototype were developed to overcome production bottlenecks [47,48]. Separation efficiency depends on residue moisture content, as excessive moisture promotes particle aggregation and hinders larva–residue separation [39]. The addition of inert materials can help optimize moisture conditions and improve separation [34]. The additives were used to reduce substrate moisture at the end of larval growth, facilitating larva–residue separation. Their selection was based on practical and logistical criteria. These included the availability of bakery waste from the supermarket supplying the FVW and the use of low-cost, easily accessible materials, such as bran and sawdust, for ethical and sustainability reasons. To the best of our knowledge, this is a novelty, since few studies have isolated the effect of the conditioning substrate on sustainability within a single feedstock [49–51].

2. Materials and Methods

2.1. Goal and Scope of the Study

The objective of this LCA is to quantify and compare the cradle-to-gate global warming potential of producing 15-day-old larvae (15DOL) of *Hermetia illucens* as an animal-protein source from FVW conditioned with three different additives. The intended application is to inform researchers and operators in the insect-rearing and feed sectors, as well as biowaste management decision-makers, on the relative environmental performance of the three substrates; accordingly, the study is framed as a comparative assessment, with uncertainty and sensitivity analyses reported [52]. The bioconversion process was carried out in a pilot laboratory plant for BSF within the laboratories of the ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) and CREA (Council for Agricultural Research and Analysis of Agricultural Economics) institutes, both located in Rome province (Italy). The potential environmental consequences resulting from the bioconversion of FVW by BSF were evaluated using the LCA methodology. LCA is a systematic approach for comprehensively evaluating potential environmental impacts associated with a product, service, or process across its entire life cycle. According to the ISO 14040-44:2006 standard, the LCA study includes four distinct phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [52,53]. Climate change (GWP100a) was selected as the reference impact category (see Section 2.3). FVW generated daily in markets across the Italian territory could represent a potential feed source for BSFL. Acknowledging the inherent heterogeneity of FVW, its nutritional profile can vary depending on the types of vegetables present [37]. Notably, the prevalent high moisture content, often exceeding 80%, poses a substantial constraint for residue separation [39]. Consequently, insect factories resort to physical treatments, such as drying or mechanical processing, to mitigate water content, albeit at the expense of increased energy and resource consumption. In this study, an innovative approach was explored to achieve analogous results by introducing additives to the FVW. These additives are intended to absorb excess water within the substrate. The system boundaries were defined by a cradle-to-gate approach, where the gate corresponds to the plant's processing stage (dried 15-day-old larvae and frass leaving the facility) including production and transportation of inputs, production of feeding substrates (transport and substrate conditioning), insect farming (production of eggs and five-day-old larvae (5DOL), rearing of 15-day-old BSFL (15DOL), and insect processing (Figure 1). LCA methodology was used to assess sustainability and compare three production scenarios of BSFL grown on three different substrates:

- Scenario 1 consisted of 80% FVW and 20% bakery waste;
- Scenario 2 consisted of 80% FVW and 20% bran;
- Scenario 3 consisted of 98% FVW and 2% wood sawdust.

In order to understand the potential benefits of insect cultivation for minimizing food waste and generating valuable substances, such as proteins for animal feed, the study utilized multiple functional units (FUs). This approach is motivated by the dual role of the system as both a waste treatment technology and a biomass production process. From a waste management perspective, the system is most appropriately evaluated per unit of treated input (1 Mg of biowaste), which provides the relevant basis for comparison with alternative treatment options, such as composting and anaerobic digestion. From a production perspective, the system is evaluated per unit of marketable output, namely, 1 kg of dry larvae and 1 kg of larval protein. The former enables direct comparison with previous black soldier fly (BSF) life cycle assessment studies [36,54–56], while the latter reflects the intended function of the larvae as a source of animal protein and facilitates comparison with conventional protein feeds, such as soybean meal. For an industrial decision oriented

to protein production, the protein-based functional unit is the most relevant, whereas the per Mg unit is the appropriate reference for a waste management decision. Reporting the results across these units is essential because the scenario ranking depends on the functional unit chosen (Section 3.2), which is one of the main findings of the study.

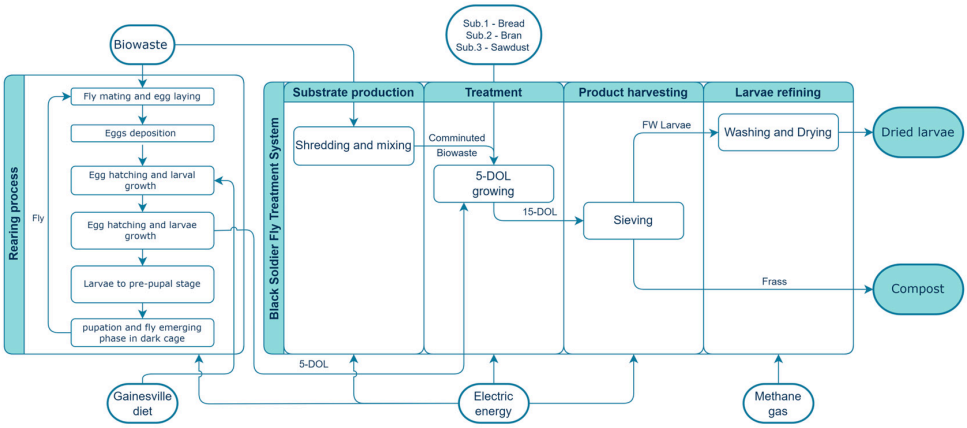


Figure 1. System boundary—dried BSFL and insect frass production.

Since bioconversion of FVW generates both insect larvae and frass as co-products of bioconversion, the system involves multifunctionality. This was addressed through economic allocation, chosen due to the large difference in market value between the two co-products. Although ISO 14044 recommends economic allocation as a last resort, it is considered appropriate when price differences are substantial [57]. Mass allocation was not used because it would assign roughly 86–95% of the burden to the low-value frass, misrepresenting a process whose purpose is to produce larvae; system expansion alone was likewise not adopted, since for these jointly produced co-products it would make the result depend entirely on the assumed marginal substitutes.

According to Salomone et al. [54], insect frass has an average value of 7.5 € Mg^{-1} and larvae at 995 € Mg^{-1}. Therefore, the full impact of bioconversion by *H. illucens* was attributed largely to dried larvae and to a lesser extent to frass, depending on the scenario, biowaste reduction, and unit price. Because the allocation relies on market prices, which are still volatile for insect-derived products, the stability of the allocation factors against price variation was tested and reported in the Supplementary Material (Table S1). To account for potential environmental benefits, avoided products were modeled using a substitution approach. These credits were applied only to the allocated share of each output, ensuring consistency between allocation and substitution. The inclusion of avoided products reflects the displacement of conventional products and their associated impacts, thus reducing the net environmental burden attributed to each co-product. Specifically, the avoided products considered were mineral fertilizers (N, P_2O_5, and K_2O) when frass is used as compost (frass is a nutrient-rich organic fertilizer with a balanced N:P:K ratio [58]), and soybean meal when dried larvae are used as animal feed. These substitutions were included across all scenarios to evaluate the environmental benefits of frass utilization. The FU of 1 kg of larval protein was additionally used to compare the bioconversion system with conventional vegetable protein production. This approach allows the substitution of protein sources used in livestock feeding, such as soybean meal, to be directly accounted for.

2.2. Life Cycle Inventory

An environmental analysis was conducted to assess the production of 15DOL from BSF, including, as foreground data, the primary data collected during tests at both research laboratories. At the ENEA laboratory, the bioconversion efficiencies of three distinct FVW-

based substrates by BSFL were examined. The resulting dataset played a pivotal role in establishing key parameters, such as mass balance, biowaste reduction rates, production, and the chemical characterization of the larvae, including their nutritional content, as well as the composition of the insect frass generated. At the CREA laboratory, primary data on energy consumption and productivity metrics were derived from trials using a semi-automatic prototype machine developed during the project [59,60]. This machine, designed specifically for the bioconversion of the substrate during the rearing of 15DOL, provided critical insights for the study. To address any data gaps in the process, background processes were modeled with the ecoinvent database (v3.0) as implemented in SimaPro 8.0.2 (Prè Consultant, Amersfoort, The Netherlands), adapted to the Italian context where possible. Data for a BSFL production cycle obtained from 1 Mg of organic waste (FVW+% additives) were considered in relation to the following five stages: substrate production, rearing process, treatment, product harvesting, and larvae refining.

2.2.1. Substrate Production

The substrate production phase plays a fundamental role in the BSF life cycle, serving as the base for the subsequent bioconversion by larvae aged 5 to 15 days. Collection of FVW from local markets and its transport to the BSF pilot plant was modeled as road freight over a one-way distance of 17 km, carried by a medium rigid lorry (16 t gross vehicle weight, EURO 4 class). A mass-limited freight dataset was used, with a default 64% load factor that already accounts for empty return trips; no separate return leg was, therefore, modeled. The applied emission factor was about 0.12 kg CO_2eq per t·km and includes fuel production (upstream), combustion during haulage, road infrastructure, and logistics operations. Transport was modeled at ambient temperature, using a standard road freight dataset, consistent with the short baseline collection distance (17 km) and the immediate on-site processing of the FVW; over such a short transit, spoilage of the perishable substrate and the associated degradation emissions are considered negligible. For the longer collection distances explored in the sensitivity analysis (Section 3.7), the absence of a spoilage term is a simplification that would add a common increment across all scenarios.

At the plant, shredding and mixing are the first process that ensures the comminution and uniformity of the substrate, optimizing conditions for bioconversion. The electricity consumption attributed to storing, shredding, and mixing 1 kg of biowaste is quantified at 0.0025 kWh, 0.1 kWh, and 0.0175 kWh, respectively [8]. During the substrate production phase, specific components were incorporated into the FVW to create distinct substrates (Substrate 1, Substrate 2, and Substrate 3), namely, Substrate 1 with 20% bakery waste, Substrate 2 with 20% bran, and Substrate 3 with 2% sawdust (on a mass basis). The aim of adding these components was to reduce the moisture content of FVW. Bakery scraps, such as bread, pizza, and pastries, were obtained from a supermarket as food waste, while bran and dry inert materials, such as sawdust, which are both by-products of the agro-industry, were purchased from a local seller. These three substrates play a critical role in the scenarios evaluated in the current study, serving as the basis for comparing different bioconversion outcomes.

2.2.2. Rearing Stage

To initiate the bioconversion process, a starter consisting of a proper quantity of eggs close to hatching or newborn larvae that are equal, homogeneous, and numerically sufficient is required. The production of the starter must be ensured by a continuous breeding cycle of mating adults and egg-laying females, obtained from mature larvae reared on a standardized production line. The rearing process constitutes a pivotal stage in

the BSFL life cycle, dedicated both to the production of the starter (typically five-day-old larvae, 5DOL) essential for subsequent treatment phases and to the maintenance of the reproductive colony. The entire BSF life cycle, encompassing egg deposition, spans a duration of 40–45 days. The bioconversion of 1 Mg of biowaste necessitates approximately 0.8 million larvae. Within this context, 8335 BSFs, comprising 5000 males and 3335 females, generate 808,335 larvae, ensuring the continual production of BSF. Maintaining optimal environmental conditions, with temperatures ranging between 27 and 28 °C and relative humidity (RH) maintained at 70–80%, alongside 16 h of light exposure for 6 days during the mating phase, is imperative for the growth of BSFs. The energy requirement to sustain these conditions is estimated at 21.7 kWh per cycle (1 Mg of biowaste). Notably, reusable polyester trays serve as the substrate for egg deposition. Upon hatching, the larvae input for this phase includes 269.8 kg of water, 8335 larvae for restocking, 6.4 kg of Substrate (1, 2 or 3), 40 polypropylene trays (0.324 kg per tray, with a lifespan of 2 years and utilization of 10 days per cycle, resulting in an impact of 0.178 kg of polypropylene per cycle), 164 kg of Gainesville diet, and 21.7 kWh of electricity for lighting and heating. The output from this rearing process yields 808,335 5DOL, crucial for the subsequent stages of the BSF life cycle. The Gainesville diet is a standard formulation consisting of 50% wheat bran, 30% alfalfa meal, and 20% corn meal according to Hogsette et al. [61], and was included in the analysis for growing larvae up to 5 days of age. Its ingredients were modeled in SimaPro 8.0.2 with the closest available ecoinvent unit processes: alfalfa meal with "Alfalfa-grass mixture, Swiss integrated production", corn meal with "Grain maize IP, at feed mill/CH", and the wheat fraction with "Wheat seed, Swiss integrated production, at regional storehouse", with the last two adopted as proxies for the milled feed fractions.

2.2.3. Treatment and Product Harvesting

In this pivotal phase of the BSF life cycle, indicated as the "Treatment phase", the bioconversion of biowaste unfolds. Here, the transformation of 5DOL into 15DOL occurs, setting the stage for the subsequent "Harvesting phase", where larvae are separated from the substrate, ultimately yielding insect frass. The harvesting phase, conducted over a 10-day cycle, is a multifunctional process with two primary outputs: the 15DOL and insect frass. Table 2 shows the outputs produced in the three scenarios and the economic allocation applied based on their economic values. The economic allocation factors (96%, 90%, and 87% to larvae in Scenarios 1–3) were derived from the unit prices given in Section 2.1 and applied uniformly to all impact categories.

Table 2. Bioconversion outputs and economic allocation for 15DOL and insect frass produced per Mg of biowaste in different scenarios, and equivalent avoided fertilizers (N and K in insect frass analyzed during the Hermes project).

Product Harvesting	15DOL	Economic Allocation	Insect Frass	Economic Allocation	Avoided Fertilizers		
Unit	kg_{FM} Mg^{-1} Biowaste	%	kg_{FM} Mg^{-1} Biowaste	%	kg N *	kg P_2O_5 **	kg K_2O ***
Scenario 1	57.3 ± 1.50	96	340	4	6.86	5.31	3.28
Scenario 2	45.8 ± 2.44	90	660	10	8.54	10.31	9.35
Scenario 3	27.8 ± 1.27	87	555	13	8.65	8.67	4.79

FM = fresh matter; * % N per amount of insect frass (DM): 2.9% (Sub1); 1.86% (Sub2); 2.24% (Sub3). ** Calculated considering 0.98% of P in the insect frass [54]. The conversion factor used to convert P to P_2O_5 is 2.29 (P_2O_5/P). *** % K per amount of insect frass (DM): 1.15% (Sub1); 1.69% (Sub2); 1.03% (Sub3). The conversion factor used to convert K to K_2O is 1.204 (K_2O/K). Avoided fertilizer amounts were computed on a dry matter basis, converting fresh frass to dry matter with a dry matter content of 69.6% [58]; in the model, these substitution credits are applied only to the economically allocated frass share (4%, 10%, and 13% in Scenarios 1–3, respectively).

The nutrient substitution credits in Table 2 were derived on a dry matter basis. Fresh frass was converted to dry matter using a dry matter content of 69.6% [58]. The nitrogen and potassium contents of the frass were determined on a dry matter basis determined during the Hermes project (Table 2, notes), whereas the phosphorus content was taken from the literature (0.98% P; Salomone et al. [54]); these were applied to the dry mass to estimate the amounts potentially substituting mineral fertilizers, with phosphorus and potassium expressed as P_2O_5 and K_2O using conversion factors of 2.29 and 1.204, respectively. The avoided fertilizer amounts quantify the mineral fertilizer inputs potentially displaced when the frass is used as an organic fertilizer; consistent with the economic allocation, this substitution credit acts only on the small share of the burden assigned to the frass (4–13%).

The inputs required for the bioconversion process of 1 Mg of biowaste, common for all scenarios, are 800,000 5DOL from the rearing process, and there is 46.8 kWh of electricity for lighting, heating, and operation of the prototype for separation of 15DOL to the substrate (harvesting phase). Additionally, 20 polypropylene trays, each weighing 0.670 kg and with a lifespan of 2 years, are employed for the cultivation of larvae. The utilization of these trays, restricted to 10 days per cycle, results in an impact of 0.184 kg of polypropylene per cycle. For the growth of 15-day-old larvae, the water consumption required was 925 kg, 739 kg, and 449 kg for Scenarios 1, 2, and 3, respectively.

2.2.4. Larvae Refining

Larvae refining stands out as the final phase of the bioconversion process, signifying the transformation of 15DOL into a market-ready form (Table 3). The process begins with fresh-weight larvae (15DOL), providing the initial material for the refining steps. The output of this refining process is the production of 15DOL that have been washed and dried to 10% moisture content. The avoided soybean meal was computed on a protein-equivalent basis, dividing the larval protein by the protein content of soybean meal. Inputs into this phase include water allocated for cleaning purposes (larvae and facilities). Drying consumed 0.04 m^3 of natural gas per kg of fresh larvae [62].

Table 3. Dry 15DOL per Mg of biowaste in different scenarios, protein and lipid content, and equivalent avoided soybean meal.

Larvae Refining	15DOL *	Protein **	Lipid **	Avoided Soybean Meal §
Unit	kg $_{(10\%M.C.)}$ Mg^{-1} Biowaste	kg Mg^{-1} Biowaste	kg Mg^{-1} Biowaste	kg Mg^{-1} Biowaste
Scenario 1	17.4	3.74	7.22	8.13
Scenario 2	13.7	4.48	3.49	9.32
Scenario 3	6.37	1.91	1.44	4.14

* Prepupae 15DOL production per scenario after the washing and drying process, per Mg of substrate bioconverted. ** Calculated on kg DM of prepupae 15DOL according to ENEA laboratory analysis. § Calculated considering 46% of the protein content of soybean meal [54].

2.2.5. Inputs and Outputs Excluded from the Study

Some minor processes were omitted in this study due to the negligible impact in relation to the goal of the research. In general, energy and water consumption associated with office use were omitted, as well as the disposal of the limited inorganic waste (plastic and paper) produced during the production of BSF. Research on BSF production has shown that the larvae can significantly reduce greenhouse gas emissions, particularly methane and nitrous oxide, during the bio-treatment of organic waste [8,12]. In this study, no direct emission of CH_4 and N_2O was considered due to larvae substrate bioconversion because, as reported by Salomone et al. [54], Diptera (like *Hermetia illucens*, L.) do not seem to be

methane-emitting insect species. Furthermore, the impact of the BSF diet on soil greenhouse gas emissions from the frass is still not fully understood [63]. Further studies are needed to explore the potential environmental benefits and drawbacks of BSF production, particularly in relation to N_2O and CH_4 emissions. For this reason, the emissions generated by frass when incorporated into the soil were not considered in this study. In a review carried out by Laurent et al. [64], it was highlighted that only 12% of LCA studies included capital goods, and as suggested by Salomone et al. [54], excluding the infrastructure will allow a comparative analysis with other conventional products. In this study, facilities, machinery, and equipment were not taken into account. This choice was made because the study is based on a pilot laboratory plant, and analyzing the impact of infrastructure would not be feasible or provide exhaustive data to explain the impacts of infrastructure on a real insect farm.

2.3. Life Cycle Impact Assessment (LCIA) of BSFL, Uncertainty, and Sensitivity Analysis

The environmental impacts of the analyzed systems were assessed with respect to the defined functional units (1 kg of dry 15DOL and 1 kg of protein). Climate change, expressed as global warming potential over a 100-year time horizon (GWP100a; IPCC 2007, v1.02), was adopted as the reference impact category to evaluate the contribution of BSFL-based biowaste conversion to greenhouse gas emissions. IPCC 2007 (AR4, GWP100a v1.02) was chosen deliberately to preserve comparability with the body of published BSF life cycle assessments, most of which report climate change results with this or with earlier characterization models (Table 4). Using the same model enables a like-for-like benchmark against previous studies; we acknowledge this as a deliberate methodological choice for comparability.

Parameter uncertainty was quantified by Monte Carlo simulation in SimaPro (1000 iterations, 95% confidence level) on the protein functional unit. Consistent with ILCD guidance for comparative, decision support studies, the compared alternatives were characterized through their reasonably best- and worst-case scenarios, and uncertainty propagation was used to test the significance of their difference; intermediate scenarios within these bounds are optional and were not simulated [65]. The simulation was, therefore, applied to the pair that bounds the comparison, the highest-impact scenario (Scenario 1, bakery waste), and the lowest-impact scenario (Scenario 2, bran). Scenario 3 (sawdust) is an intermediate case: the three systems share an identical foreground model, the same background datasets, and the same characterization method, and they differ only in the conditioning additive, so the deterministic protein footprint of Scenario 3 falls between the two simulated distributions, and its ranking position is already bounded by them. A scenario-based sensitivity analysis was then performed on the collection distance, the most site-specific parameter, by recomputing the per Mg footprint at one-way distances of 17, 50, 100, and 200 km. All other inputs were held at their baseline values, and the transport increment was added as 0.12 kg CO_2eq t·km^{-1} multiplied by the distance [66].

Table 4. Global warming potential of BSFL bioconversion reported in the literature by functional unit, production scale, and substrate type.

Studies	Unit	Scale of Production/ Assessment	Impacts		
			Control Diet	Food Processing By-Product/Food Waste	Manure Diet
Bava et al. [36]	1 kg DM whole	Lab: 1000 larvae per batch	CC: 5.76	CC: 0.7–2.0	n/a
Bosch et al. [51]	1 kg of protein	Lab: 100–1000 larvae per batch	GWP: 4–7	GWP: 1–5	GWP: 1–7

Table 4. *Cont.*

Studies	Unit	Scale of Production/ Assessment	Impacts		
			Control Diet	Food Processing By-Product/Food Waste	Manure Diet
Joensuu et al. [67]	FU1: 1 kg WM whole larvae; FU2: 1 kg of protein	Based on Oonincx et al., 2015 [68]; Oonincx and de Boer, 2012 [69]	FU1: GWP2: 3.1 FU2: GWP2: 23–27	FU1: GWP2: 3.1	n/a
Ites et al. [55]	1 kg DM whole larvae *	Pilot mobile: 12.7–64 tons of insects annually	n/a	GWP1: −6.42 to 2.0	n/a
Komakech et al. [56]	1 kg DM whole	Industrial hypothetical	n/a	GWP2: 0.29	n/a
Roffeis et al. [70,71]	1 kg DM whole larvae	Pilot: 3.5–4.4 tons DM larvae annually	n/a	GWP3: 4.5–12	
Salomone et al. [54]	1 kg DM whole larvae *	Pilot industrial: 110–329 tons DM larvae annually	n/a	GWP4: 1.0	n/a
Smetana et al. [72]	1 kg DM dried defatted powder	Pilot industrial: 50 tons insect flour	GWP1,3: 1.36–15.1		
Smetana et al. [73]	1 kg DM margarine (insect lipids)	Based on [62,74]	n/a	GWP1: 2.4–4.1	n/a

CC = climate change in kg CO_2eq (ILCD 2011); DM = dry matter basis; GWP = global warming potential in kg CO_2eq (not specified method); GWP1 = global warming potential in kg CO_2eq (IMPACT2002+); GWP2 = global warming potential 100 years in kg CO_2eq (separate indicator); GWP3 = global warming potential in kg CO_2eq (ReCiPe); GWP4 = global warming potential in kg CO_2eq (IPCC 2007). * Recalculated for 1 kg DM of whole BSFL. n/a= not available.

3. Results and Discussion

3.1. Bioconversion Outputs and Larval Yields

The three substrates differed markedly in how much biomass they returned per unit of treated waste. Per Mg of biowaste, fresh 15-day-old larvae (15DOL) reached 57.3 ± 1.50 kg in Scenario 1 (20% bakery waste), 45.8 ± 2.44 kg in Scenario 2 (20% bran), and 27.8 ± 1.27 kg in Scenario 3 (2% sawdust). After washing and drying to 10% moisture, these yields corresponded to 17.4, 13.7, and 6.37 kg of dry larvae per Mg of waste, respectively. The same ranking held for the co-product: insect frass amounted to 340, 660, and 555 kg per Mg of waste across the three scenarios. Because the larvae account for nearly all of the market value, the economic allocation assigned 96%, 90%, and 87% of the environmental burden to the larval fraction, with the remainder allocated to the frass.

Protein and lipid contents did not follow larval mass. Scenario 2 produced the highest protein per kg of dry larvae (358 g, against 237 g in Scenario 1 and 329 g in Scenario 3) as well as per Mg basis (4.48 kg Mg^{-1} of biowaste, against 3.74 and 1.91 kg Mg^{-1} of biowaste for Scenarios 1 and 3). Concerning the lipids, Scenario 1 was the richest (7.22 kg Mg^{-1} of biowaste), followed by Scenario 2 (3.49 kg Mg^{-1} of biowaste) and, finally, Scenario 3 (1.44 kg Mg^{-1} of biowaste). The bran substrate, therefore, combined a moderate biomass yield with the highest protein concentration, whereas the bakery waste substrate maximized lipid accumulation and the sawdust substrate lagged on every nutritional metric. This separation between mass yield and nutritional quality is the reason the functional unit matters so much for the comparison that follows.

3.2. Carbon Footprint Across Functional Units

Global warming potential (GWP100a, IPCC 2007) was calculated for four functional units: 1 Mg of treated biowaste, 1 kg of fresh larvae, 1 kg of dry larvae, and 1 kg of larval protein. The chosen reference value reverses the ranking of the scenarios, which is the central result of this study (Figure 2).

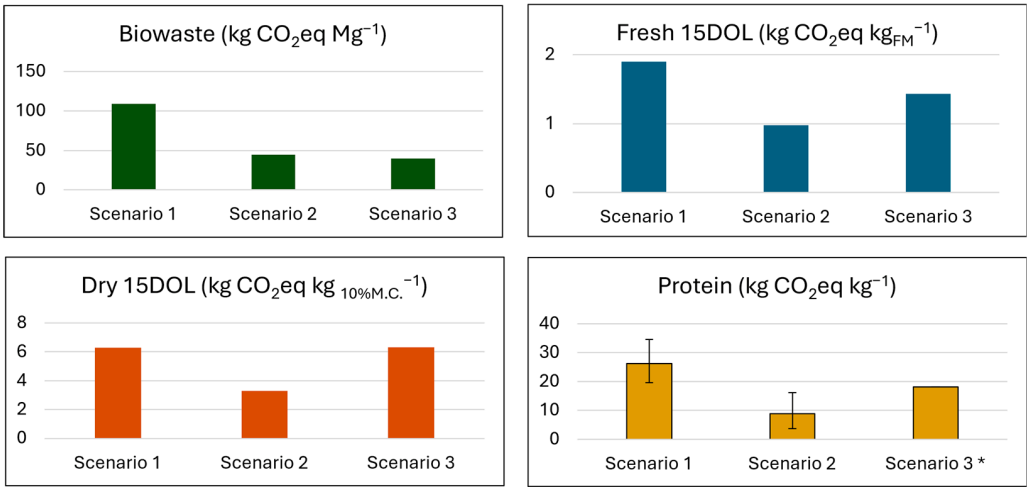


Figure 2. Global warming potential (GWP100a, IPCC 2007) per functional unit. Scenario 1 consisted of 80% FVW and 20% bakery waste; Scenario 2 consisted of 80% FVW and 20% bran; Scenario 3 consisted of 98% FVW and 2% wood sawdust. Error bars on the protein panel represent the 95% confidence interval from the Monte Carlo simulation (1000 iterations) for Scenarios 1 and 2. Scenario 3 (*) was treated deterministically and is shown without an error bar (see Section 2.3).

As reported in Figure 2, Scenario 1 showed substantially higher emissions compared to the other scenarios (except when the FU is 1 kg of dry larvae). In particular, on a biowaste basis, GWP was about 142% and 174% higher compared to Scenario 2 and Scenario 3, respectively. Based on this criterion, the sawdust substrate exhibited the lowest environmental impact, whereas the bakery waste substrate showed the highest, with Scenario 3 resulting in an impact approximately 11% lower than Scenario 2. The carbon-intensive bakery waste additive drives the high value of Scenario 1, because bakery waste carries a substantial embodied footprint while bran is a low-value milling by-product and sawdust is close to burden-free. The ranking changes when the functional unit is shifted to the marketable product. When expressed per kilogram of fresh and dry larvae, the environmental impacts of the three scenarios become much more similar. In particular, the impact of producing 1 kg of dry larvae was found to be 6.29, 3.31, and 6.33 kg CO_2eq for Scenarios 1, 2, and 3, respectively. In the second scenario, the use of this FU leads to an estimated 47% reduction in comparison with both the first and third scenarios. When expressed per kilogram of protein, Scenario 2 demonstrated the lowest emissions (8.87 kg CO_2eq), in comparison with 26.20 kg CO_2eq for Scenario 1 and 18.20 kg CO_2eq for Scenario 3. Relative to Scenario 1, the bran substrate reduces the protein carbon footprint by approximately 66%, and by approximately 51% compared with Scenario 3. The low productivity of the sawdust substrate, which looked advantageous per Mg of biowaste, becomes a penalty once the burden is spread over a small protein output. Scenario 2 wins on the protein basis because it pairs a moderate process burden with both the largest protein yield and the highest protein concentration. The GWP per FU obtained in this study is consistent with other studies that have assessed the impact of bioconversion of biowaste by BSFL on climate change (Table 4).

Across the studies reported in Table 4, the carbon footprint of BSFL spans a wide range, from slightly negative values to about 27 kg CO_2eq per functional unit, reflecting differences in feedstock, production scale, system boundaries, and the impact assessment method applied. The protein-based values reported in the present study (8.87–26.20 kg CO_2eq kg^{-1}) fall within the upper part of the protein range reported by Bosch et al. [51] and Joensuu et al. [67], consistent with the pilot laboratory scale of the present study system and the burden of the starter diet, which an industrial line would dilute over a far larger throughput. The dry larvae values (3.31–6.33 kg CO_2eq kg^{-1}) are comparable to those of other pilot-scale studies [68–70] and higher than industrial-scale estimates [54,56], in line with the expected economies of scale.

3.3. Contribution Analysis and Hot Spots

A contribution analysis of the foreground inventory identifies where the emissions accumulate. For Scenario 1, three processes account for roughly 95% of the gross foreground burden: electricity for storing, shredding, mixing, lighting, heating, and the separation prototype (about 38%); the substrate additive, which here is bakery waste (about 34%); and the Gainesville starter diet, which is used to rear the colony to the 5-day-old stage (about 24%). Natural gas for drying, transport over the 17 km collection distance, water, and polypropylene trays together contribute to the residual few percent. The same structure applies to Scenarios 2 and 3, but the additive term shrinks sharply because bran and sawdust carry far smaller emission factors than bakery waste, which is why the per Mg footprint of those two scenarios is less than half compared to Scenario 1. This ordering matches the consensus in the wider literature, where the rearing substrate is repeatedly reported as the dominant contributor to the environmental impact of insect-based products [36,71,75]. Energy demand constitutes the second significant lever in pilot-scale systems, such as the present one, in accordance with screening studies of waste-to-product chains, in which production-stage electricity is identified as a primary area of high demand [76].

3.4. Effect of the Rearing Substrate

The additional component is the variable that distinguishes the three scenarios, and it acts on two fronts at once. It changes the process burden because the embodied emissions of bakery waste, bran, and sawdust differ by roughly an order of magnitude, and it changes the denominator of the product-based functional units because each additive supports a different larval yield and nutritional profile. Sawdust minimizes the added burden but starves the system of biomass and protein; bakery waste maximizes biomass and lipid but at a heavy carbon cost, while bran sits between the two and gives the best protein-based outcome.

This trade-off between a low-footprint substrate and the productivity it can sustain is well documented for black soldier fly larvae. High-quality, grain-rich substrates accelerate larval growth but are associated with a higher environmental footprint and may compete with food and feed applications. In contrast, low-value side streams can reduce the environmental footprint, although they may slow larval development and decrease biomass yields, potentially offsetting the expected environmental benefits [77]. The results of this study demonstrate the ability to reproduce the observed tension within a single feedstock by varying only the conditioning additive. Furthermore, this study shows that the additive choice, rather than the fruit and vegetable waste itself, governs the comparison.

3.5. Benchmarking Against Composting and the LCA Literature

Set against alternative treatments of the same waste, the bioconversion route performs well on climate change. Composting of biowaste has been reported at about 111 kg CO_2eq per Mg, driven largely by direct CH_4 and N_2O emissions during the process [78].

Scenario 1 is close to this figure, but Scenarios 2 and 3 sit roughly 60% lower, which supports the view that BSF treatment can reduce climate impact relative to composting when the substrate is conditioned with a low-footprint additive. The per Mg values also fall within the broad envelope reported across published BSF assessments. A recent critical review of twelve life cycle assessments placed emissions from treating one ton of biowaste with insects between −432 and 877 kg CO_2eq, with an average near 70 kg CO_2eq, and attributed much of this spread to differences in system boundaries: low values often omit substrate collection, larvae production, pre-treatment, or transport, while high values include facility construction and frass processing [77]. The same review notes that GHG estimates for BSF farming can differ by a factor of up to twelve between studies, and that anaerobic digestion can outperform BSF on global warming potential. Our results, which include collection, rearing, processing, and transport but exclude infrastructure, fall within the lower-to-middle part of this range. Our results should, therefore, be interpreted considering the methodological choices underlying each assessment, rather than as absolute performance indicators. Process-level comparisons point in the same direction. A carbon footprint of 0.506 kg CO_2eq per kg of fresh BSFL has been reported for production fed on organic waste [79]. The fresh-larvae values obtained in this study range from 0.98 to 1.90 kg CO_2eq per kg.

3.6. Uncertainty and Significance Analysis

The GWP of the protein functional unit was characterized with a Monte Carlo simulation (1000 runs) in SimaPro, propagating the inventory uncertainty through the IPCC 2007 model, comparing the results of the best and the worst scenarios. For Scenario 1, the protein GWP had a mean of 26.2 kg CO_2eq, a median of 25.9, a standard deviation of 3.8, and a coefficient of variation (CV) of 14.5%, with a 95% interval of 19.5–34.9 kg CO_2eq. For Scenario 2, the same indicator reconstructed from the simulation had a mean near 8.95 kg CO_2eq, a standard deviation of about 3.15, a CV of roughly 35%, and a 95% interval of about 3.7–16.2 kg CO_2eq. The larger relative spread of Scenario 2 reflects its smaller protein yield denominator, which amplifies the propagated uncertainty even though its central value is far lower. The comparison between Scenario 1 and Scenario 2 is robust: their 95% intervals do not overlap (the upper bound of Scenario 2, about 16.2, lies below the lower bound of Scenario 1, 19.5), so the difference in protein carbon footprint is discernible at the 95% level.

The sensitivity of the economic allocation factors to co-product prices was tested by varying both the larvae and frass unit prices by ±50% (Supplementary Table S1). The larval fraction remained the dominant recipient of the burden across the whole price range—from 96%, 90%, and 87% at the baseline (Scenarios 1–3) to no less than 88%, 75%, and 69% under the most adverse price combination, and the ordering of the allocation factors was preserved throughout. The product-based scenario ranking is, therefore, robust to realistic price variation.

3.7. Sensitivity Analysis

The sensitivity analysis focused on transport distance, the most site-specific parameter, and the one that most affects the transferability of the results from the pilot plant to a full-scale collection network. The carbon footprint per Mg of biowaste was recomputed for one-way distances of 17, 50, 100, and 200 km, holding all other inputs at their baseline values and adding the transport increment (Table 5).

At the 17 km baseline, transport contributes about 2 kg CO_2eq Mg^{-1}, only a few percent of the footprint. Extending the radius to 100 km raises the Scenario 1 footprint by about 9%, but by about 22% and 25% in Scenarios 2 and 3: although the absolute increment is identical across scenarios, the smaller foreground of the bran and sawdust substrates makes them proportionally more sensitive to haulage. Taking composting (about 111 kg

CO_2eq Mg^{-1} [78]) as an external reference, Scenario 1 reaches parity at 34.75 km, whereas Scenarios 2 and 3 remain below it up to 568 and 611 km. On the protein functional unit, the ranking of the three substrates is unchanged across the whole distance range. The climate advantage of the two low-footprint additives is, therefore, robust to any realistic collection distance, while the bakery waste substrate loses its parity with composting after a short haul. The composting value refers to a different system boundary and is used only as an indicative benchmark.

Table 5. Global warming potential (GWP100a, kg CO_2eq Mg^{-1} biowaste) as a function of one-way collection distance.

Distance (km)	Sc1 (Bakery Waste)	Sc2 (Bran)	Sc3 (Sawdust)
17	108.87	44.88	39.75
50	112.83	48.84	43.71
100	118.83	54.84	49.71
200	130.83	66.84	61.71
300	142.83	78.84	73.71
400	154.83	90.84	85.71
500	166.83	102.84	97.71
600	178.83	114.84	109.71
700	190.83	126.84	121.71

Transport increment computed as 0.12 kg CO_2eq $t{\cdot}km^{-1}$ over the baseline distance; all other inputs held constant. Approximate break-even with composting (≈111 kg CO_2eq Mg^{-1}).

3.8. Commercial-Scale Scalability

The present assessment refers to a pilot laboratory plant, and its absolute values should not be read as industrial performance. Two of the three main contributors, the Gainesville starter diet and the energy-intensive pilot equipment, are amortized over a small throughput and would be substantially diluted in a continuous, commercial-scale operation, consistent with the lower dry larvae footprints reported for industrial systems [53,55]. Scaling up would, therefore, lower the absolute footprints per kg of larvae and protein, chiefly by reducing the electricity and starter diet shares. However, the comparison between substrates is expected to persist because the difference that drives it (the embodied emissions of the conditioning additive) is an intrinsic property of the additive and largely independent of scale. On the other hand, as electricity and starter diet terms shrink, the additive would become relatively more dominant, reinforcing the central finding. Scale would also affect ancillary aspects like collection logistics over a larger network (explored in Section 3.7) and the maturity of the frass market (tested in Supplementary Table S1), but neither overturns the ranking. A dedicated industrial-scale assessment remains a priority for future work.

4. Conclusions

The present study assessed the environmental feasibility of producing 15-day-old *Hermetia illucens* larvae as a protein source in a pilot plant in central Italy and asked whether the conditioning additive blended with fruit and vegetable waste changes that feasibility. The study examined three substrates differing only in additive (20% bakery waste, 20% bran, 2% sawdust) and determined whether the identification of the lowest-impact option depends on how the output is measured. The central finding is that the ranking of the scenarios depends on the functional unit. Per Mg of treated waste, the sawdust substrate is the lowest-impact option (39.75 kg CO_2eq), just below the bran substrate (44.88 kg CO_2eq) and well below the bakery waste substrate (108.87 kg CO_2eq). Per kg of protein, the order reverses: the bran substrate is best (8.87 kg CO_2eq), about 66% below bakery waste and 51% below sawdust, because it combines a moderate process

burden with the highest protein yield and concentration. Electricity, the additive, and the starter diet are the main foreground contributors, and the additive is the variable that separates the scenarios. The Monte Carlo analysis shows that the advantage of the bran over the bakery waste substrate (best vs. worst scenarios) is discernible at the 95% level (non-overlapping intervals). Against composting (about 111 kg CO_2eq Mg^{-1}), the bran and sawdust substrates cut climate impact by roughly 60%, and this advantage is robust across realistic collection distances. This study contributes to the literature in two important ways. First, it isolates the effect of the conditioning additive within a single feedstock, whereas most BSF assessments vary the feedstock itself, showing that the additive, rather than the fruit and vegetable waste, governs the comparison. Second, it explicitly demonstrates how the choice of functional unit can reverse a sustainability ranking, reinforcing the recognized dependence of insect–LCA outcomes on substrate choice and system boundaries.

Several limitations qualify these conclusions. Only global warming potential was used to compare the scenarios; a single-category reading cannot capture water, land, toxicity, or eutrophication burdens, which may rank the substrates differently. Infrastructure, machinery, and equipment were excluded, which is appropriate for a pilot system but understates the footprint of a full-scale facility. Direct CH_4 and N_2O emissions from bioconversion and from frass applied to soil were not modeled, and insect frass field emissions remain poorly constrained. The Monte Carlo simulation was applied to the two bounding scenarios (best and worst); Scenario 3 is an intermediate case, treated deterministically and consistent with ILCD guidance for comparative studies. The study's central conclusions, therefore, rest on the two fully simulated scenarios.

The use of bakery waste requires careful and in-depth consideration. Large retail chains tend to produce waste that fails to meet customer demands in terms of variety, texture, and freshness. This waste may result from purchasing excessive quantities that no longer meet aesthetic standards or from damaged packaging [80,81]. In the case of bakery waste, there may also be ethical considerations. Despite the challenges posed by bureaucracy and logistics, the practice of donating surplus bread to charities, food banks, and other organizations that support people in need is becoming increasingly common. This is particularly prevalent among retailers and large stores [82,83]. The donation aspect creates a positive impression on consumers [84], and as a result, producers, who are particularly mindful of ethical issues, may be reluctant to supply bakery waste. For this reason, their availability may vary in terms of both quantity and quality, as bakery waste may include products with a high fat content (such as pizza) or a high carbohydrate content (such as pastries).

Future work should extend the comparison to a full multi-category assessment across all three scenarios and scale the inventory from the pilot line to industrial throughput, where energy and equipment burdens are spread over a far larger output. Measuring direct process and frass emissions would close the largest remaining data gap, and decarbonizing the electricity supply is the most promising route to lowering the footprint of a scaled-up plant. Pairing this environmental assessment with an economic analysis and social life cycle assessment would complete the feasibility picture for retail-sourced fruit and vegetable waste.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app16178355/s1, Table S1. Sensitivity of the economic allocation factor (share of the environmental burden assigned to the larval co-product) to variation in the market prices of larvae and frass, for the three scenarios.

Author Contributions: Conceptualization, A.S. and E.S.; methodology, A.S.; software, A.S.; validation, E.S., S.A., and M.R.; formal analysis, A.S.; investigation, A.S., E.S., S.A., C.B., M.R., A.D.G., and A.A.; resources, A.S. and S.A.; data curation, A.S., E.S., S.A., and C.B.; writing—original draft preparation, A.S., E.S., and S.A.; writing—review and editing, A.S., E.S., S.A., M.R., and C.B.; visualization, A.S. and E.S.; supervision, A.S. and E.S.; project administration, A.A., E.S., C.B., and S.A.; funding acquisition, A.A. and S.A. All authors have read and agreed to the published version of the manuscript.

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