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Bioconversion of Sugar Beet Pulp by Black Soldier Fly (*Hermetia illucens*) Larvae: Nutritional Balancing via Molasses and In-Situ Fungal Inoculation

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Abstract

Agro-industrial by-products such as sugar beet pulp (SBP) represent a substantial environmental and logistical challenge if not valorized within the circular bioeconomy. This study evaluated the bioconversion performance and waste reduction efficiency of black soldier fly (*Hermetia illucens* L.) larvae reared on SBP-based diets across three independent biological cycles ($n = 9$ replicate containers per dietary treatment, total $N = 36$ experimental units, each initially stocked with 6000 larvae). Four dietary formulations were compared on a dry matter (DM) basis: Control (100% wheat bran), Option 1 (60% wheat bran + 40% SBP), Option 2 (60% wheat bran + 40% SBP inoculated with *Trichoderma* sp. at 1×10^6 colony-forming units (CFU)/g), and Option 3 (co-diet: 60% wheat bran + 30% SBP + 10% industrial molasses). Dietary formulation significantly affected all measured biological growth and waste reduction parameters ($p < 0.05$). Inclusion of 40% unsupplemented or fungal-inoculated SBP (Options 1 and 2) suppressed wet daily larval growth rate (12.65–12.83 mg/d) and impaired the feed conversion ratio (FCR 5.75–5.87) compared to the Control (15.72 mg/d; FCR 4.68), which is attributed to dietary protein dilution and high structural fiber density. Direct in situ inoculation with *Trichoderma* sp. yielded a modest increase in substrate mass reduction (SMR 53.04 ± 2.49% vs. 47.52 ± 2.67% in Option 1) but did not improve larval growth or feed conversion. In contrast, the co-diet formulation combining 30% SBP with 10% molasses (Option 3) achieved the highest larval survival rate (93.0 ± 1.8%), elevated daily wet growth rate (16.32 ± 0.83 mg/d; 3.26 mg DM/d), lowest FCR (4.52 ± 0.23), maximum substrate mass reduction (SMR 78.60 ± 2.15%), and peak biomass conversion efficiency (BCR 22.12 ± 1.13%), performing comparably to or outperforming the wheat bran Control. These findings demonstrate that simultaneous soluble carbohydrate enrichment and fiber reduction represent an effective dietary optimization strategy for valorizing high-fiber agro-industrial side-streams in commercial insect rearing systems.

Keywords: *Hermetia illucens*; bioconversion efficiency; sugar beet pulp; molasses; *Trichoderma* sp.; circular bioeconomy; waste reduction; feed conversion ratio

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1. Introduction

Industrial agro-food processing generates millions of metric tons of organic side-streams annually worldwide, representing a major logistical, financial, and environmental challenge when managed through landfilling or open composting [1]. In Europe, sugar beet pulp (SBP)—the fibrous co-product remaining after sucrose extraction from *Beta vulgaris* L.—is generated in large quantities during seasonal autumn harvesting campaigns [1,2]. Traditionally, wet SBP is utilized as low-cost livestock feed for ruminants or channeled into anaerobic digestion facilities for biogas generation [1,2]. However, fresh SBP exhibits an inherently high moisture content (75–82%), accelerating spontaneous microbial decomposition, leachate formation, and odor emissions during storage [2,3]. While thermal dehydration stabilizes SBP for storage and transport, drying requires approximately 4.5–6.0 MJ per kilogram of evaporated water, incurring substantial energy consumption and associated carbon emissions [3–7].

Beyond insect bioconversion, recent bioengineering efforts have investigated alternative biological pathways to valorize agro-industrial and food-processing by-products into high-value biocompounds. For example, acidogenic fermentation of food side-streams has been successfully established to yield carboxylates, biohydrogen, and platform chemicals [8], while two-stage pilot systems demonstrate the production of bio-based plastics such as polyhydroxyalkanoates (PHAs) using mixed microbial cultures fed on fermented food residues [9]. Positioning insect rearing within this broader valorization landscape provides a complementary, highly efficient strategy focusing directly on feed-grade protein and lipid production [10,11].

From a nutritional and chemical perspective, the dry matter (DM) of SBP consists predominantly of structural polysaccharides (22–30% cellulose, 24–32% hemicellulose, and 20–30% pectin) but is substantially limited in crude protein (7–10% DM) and available lipids (<1.5% DM) [12–14]. The tight intermolecular cross-linking among cellulose microfibrils, arabinogalactan-rich hemicellulose matrices, and highly branched pectin polymers confers high physical recalcitrance, impeding conventional enzymatic hydrolysis [10,14]. Converting these recalcitrant fiber polymers into animal feed components requires biorefinery approaches that circumvent the thermodynamic inefficiencies of direct combustion or simple composting [10,14].

Bioconversion using black soldier fly (BSF, *Hermetia illucens* L.; Diptera: Stratiomyidae) larvae has emerged as a premier circular economy technology capable of closing nutrient loops [15,16]. *H. illucens* larvae rapidly consume organic side-streams, converting heterogeneous biomass into larval tissue suitable for poultry, swine, and aquaculture feeds [11,15,17]. By substituting for conventional feed inputs like imported soybean meal and marine fishmeal, insect farming contributes directly to the United Nations Sustainable Development Goals, specifically Sustainable Development Goal 2 (SDG; Zero Hunger—by enhancing sustainable animal feed production) and SDG 12 (Responsible Consumption and Production—by diverting agro-industrial residuals into circular production cascades) [18–20].

However, the capacity of *H. illucens* larvae to digest high-fiber agro-industrial side-streams is fundamentally constrained by their physiological and biochemical profile. Larvae possess an alkaline midgut adapted primarily to digesting proteins and non-structural starches, whereas their endogenous cellulolytic and pectinolytic enzyme machinery remains limited [21–23]. Although gut commensal microflora contribute partially to polysaccharide breakdown, raw lignocellulosic and pectin-rich substrates often extend larval development time and lower feed conversion efficiency unless balanced with complementary nutrients [21,22,24]. In particular, unfermented pectin exhibits exceptional water-absorption and swelling capacities, forming viscous hydrogels that increase the bulk shear

viscosity of the ingested mash. This rheological shift can mechanically impair the peristaltic mixing within the larval digestive tract and hinder the passive diffusion of nutrient molecules to the midgut brush border epithelium [21,22].

To address these physical, mechanical, and enzymatic bottlenecks, two primary substrate-modification interventions are commonly proposed: biological inoculation using lignocellulolytic microorganisms (e.g., *Trichoderma* sp.) and nutritional co-digestion with energy-dense side-streams [25–27]. *Trichoderma* species secrete an extensive cocktail of extracellular cellulases, endoglucanases, cellobiohydrolases, and pectinases capable of softening plant cell wall structures and hydrolyzing glycosidic bonds [26]. Fungal-assisted valorization can be conducted either via decoupled solid-state pre-fermentation or direct in situ co-inoculation. While decoupled pre-fermentation requires dedicated incubation vessels, energy input, and prolonged residence time, direct in situ inoculation offers substantial operational simplicity for commercial-scale rearing if microbial degradation can proceed concurrently with larval feeding. Concurrently, industrial molasses—a viscous by-product of sugar refining rich in sucrose, glucose, and fructose—provides rapidly metabolizable, soluble carbohydrates capable of fulfilling immediate larval metabolic maintenance requirements, mitigating amino acid oxidation for energy, and stimulating metabolic activity in the gut microbiome [12,28].

Although *H. illucens* bioconversion has been investigated on diverse agro-industrial residues (such as brewers' spent grains, fruit pomace, and agricultural wastes), direct comparative data regarding the bioconversion kinetics of sugar beet pulp remain limited. In particular, empirical studies directly evaluating unsupplemented SBP against in situ fungal inoculation (*Trichoderma* sp.) and soluble carbohydrate co-supplementation (molasses) under standardized, replicated commercial batch conditions are lacking.

The objective of this study was to evaluate the bioconversion efficiency, growth kinetics, and substrate mass reduction in *H. illucens* larvae reared on SBP-containing diets across four standardized formulations: a standard wheat bran control, an unsupplemented SBP formulation (40% SBP), a fungal-inoculated formulation (40% SBP + *Trichoderma* sp.), and a co-diet formulation (30% SBP + 10% molasses). This study focuses on gravimetric mass-balance conversion, growth kinetics, and waste reduction indices; biochemical proximate composition and fatty acid profiles are evaluated in a companion study. We hypothesized that balancing high-fiber SBP with soluble carbohydrates in combination with reduced fiber proportion would mitigate nutritional and physical constraints, resulting in improved growth performance, feed conversion, and substrate mass reduction.

2. Materials and Methods

2.1. Larval Source and Substrate Characterization

Five-day-old *H. illucens* larvae were obtained from the certified commercial breeding colony of UAB Insectum (Kaunas, Lithuania). Larvae were separated from the nursery starter feed by gentle manual sieving. The initial individual larval wet weight (10.0 ± 0.3 mg, corresponding to an initial dry matter mass of 2.80 ± 0.08 mg per larva) was determined by gravimetrically weighing and oven-drying representative sub-samples at 105 °C to constant mass [29,30]. To avoid manual handling stress and maintain accuracy across large numbers, the target stocking density of 6000 larvae per container was achieved gravimetrically: three sub-samples of 200 larvae were weighed on an analytical balance (±0.1 mg; KERN & Sohn GmbH, Balingen, Germany) to determine the exact batch mean larval weight, and the biomass equivalent to 6000 larvae (~60.0 g wet mass) was allocated to each experimental container in accordance with standard rearing protocols [30,31].

Fresh pressed sugar beet pulp (SBP) and industrial sugar beet molasses were obtained directly from the processing facility Nordic Sugar Kėdainiai (Kėdainiai, Lithuania).

Standard wheat bran was sourced from AB Kauno Grūdai (Kaunas, Lithuania). Baseline nutritional characteristics of the raw feedstocks (DM basis) were as follows:

- Fresh SBP: 21.6 ± 1.2% DM; DM composition: 9.1 ± 0.4% crude protein, 1.2 ± 0.1% ether extract, 28.5 ± 1.1% cellulose, 26.2 ± 1.0% hemicellulose, 24.1 ± 1.3% pectin, and 4.2 ± 0.3% crude ash.
- Wheat bran: 87.8 ± 0.5% DM; DM composition: 15.8 ± 0.5% crude protein, 4.1 ± 0.2% ether extract, 10.8 ± 0.6% cellulose, 24.5 ± 0.8% hemicellulose, 1.1 ± 0.1% pectin, and 5.2 ± 0.2% crude ash.
- Molasses: 74.5 ± 0.8% DM; DM composition: 8.5 ± 0.3% crude protein, 0.1 ± 0.0% ether extract, 64.2 ± 1.5% total soluble sugars (sucrose, glucose, fructose), and 9.4 ± 0.4% crude ash.

For the fungal treatment, a commercial preparation containing viable conidia of *Trichoderma* sp. (1×10^6 colony-forming unit (CFU)/g dry substrate; Bioenergy LT, Panevėžys, Lithuania) was incorporated into the dry blend prior to hydration. Conidia were mixed into the hydrated blend immediately prior to larval stocking to assess a single-step in situ protocol without an external solid-state pre-incubation phase.

2.2. Experimental Design and Dietary Formulations

Four experimental dietary treatments were evaluated on a dry matter (DM) basis (Table 1):

- Control: 100% Wheat Bran (standard commercial rearing substrate).
- Option 1: 60% Wheat Bran + 40% SBP.
- Option 2: 60% Wheat Bran + 40% SBP + *Trichoderma* sp. (1×10^6 CFU/g DM).
- Option 3: 60% Wheat Bran + 30% SBP + 10% Molasses.

Table 1. Formulation and ingredient composition of the experimental diets for *H. illucens* larvae (dry matter basis).

Treatment	Wheat Bran (% DM)	Sugar Beet Pulp (% DM)	Molasses (% DM)	Inoculant/Additive
Control	100	0	0	None
Option 1	60	40	0	None
Option 2	60	40	0	*Trichoderma* sp. (1×10^6 CFU/g)
Option 3	60	30	10	None

Note: All experimental diets were adjusted to an initial moisture content of 70.0 ± 2.0% using distilled water prior to larval stocking.

Ventilated polypropylene containers (40 × 30 × 22 cm; internal floor area 1200 cm^2) were stocked at a density of 5 larvae/cm^2 (6000 larvae per container). Substrate was supplied once at the onset of rearing following a single-batch feeding regime at an allocation of 0.60 g wet diet per larva (0.18 g DM/larva, corresponding to 3600.0 g wet diet and 1080.0 g DM per container) [29,30,32].

Rearing was conducted in a climate-controlled chamber at 28.0 ± 0.5 °C and 70.0 ± 2.0% relative humidity under complete darkness. Substrate moisture was monitored gravimetrically throughout the 18-day feeding trial and maintained at 70.0 ± 2.0% by periodic fine misting with distilled water, ensuring that moisture was not a limiting factor. Three sequential, independent biological rearing cycles were conducted:

Cycle 1: 30 May 2025–16 June 2025

Cycle 2: 28 July 2025–15 August 2025

Cycle 3: 8 September 2025–25 September 2025

Each cycle evaluated all four treatments in triplicate (3 containers × 4 treatments = 12 containers per cycle), providing $n = 9$ independent biological replicates per dietary treatment (overall $N = 36$ experimental units).

2.3. Harvesting Protocol and Sample Processing

Larvae were harvested on day 23 of total development (5 days post-hatch nursery phase + 18 days of dietary rearing), corresponding to the appearance of the earliest prepupae (<1–2% cuticular melanization) [33]. In line with commercial whole-larva harvesting procedures, larvae were harvested without a pre-harvest fasting period.

Larval biomass was separated from residual frass using automated vibrating sieves (2.5, 2.0, and 1.5 mm). Larvae were transferred onto a 3 mm washing mesh, rinsed with cold tap water, and immersed five times in clean water baths (<60 s total immersion) to remove adhering residues without causing osmotic water absorption, followed by a rinse with distilled water. Cleaned larvae were placed on paper-lined trays and exposed to gentle forced-air ventilation at 35–40 °C for 1 h to remove surface water. Sub-samples of clean larvae and residual frass were dried in a forced-air oven (Memmert GmbH + Co. KG, Schwabach, Germany) at 65 °C for 24 h and subsequently at 105 °C for 4 h to determine absolute DM content. Total live survivor counts per container were determined by weighing total live larval wet mass per container and enumerating five representative subsamples of ~200 larvae to calculate individual mean weight and extrapolate total survivor numbers (N_f).

2.4. Performance and Bioconversion Metrics

All growth, mass-balance, and conversion metrics were calculated using established mass-balance formulas [34,35]:

$$\text{Survival Rate (SR, \%)} = \left(\frac{N_f}{N_i}\right) \times 100 \quad (1)$$

where N_f is the final count of live larvae and N_i is the initial count of seeded larvae ($N_i = 6000$).

$$\text{Daily Larval Growth Rate, wet basis (DLGR}_{\text{wet}}\text{, mg/d)} = \frac{W_{f,\text{ind}} - W_{i,\text{ind}}}{t} \quad (2)$$

where $W_{f,\text{ind}}$ and $W_{i,\text{ind}}$ are the final and initial wet weights per individual larva (mg), respectively, and t is the feeding duration ($t = 18$ days).

$$\text{Daily Larval Growth Rate, dry basis (DLGR}_{\text{dry}}\text{, mg DM/d)} = \frac{m_{f,\text{ind}} - m_{i,\text{ind}}}{t} \quad (3)$$

where $m_{f,\text{ind}}$ and $m_{i,\text{ind}}$ are final and initial dry matter weights per individual larva (mg DM), respectively.

$$\text{Feed Conversion Ratio (FCR)} = \frac{W_i}{B_f - B_i} \quad (4)$$

where W_i is the total initial substrate dry mass provided (g DM, 1080.0 g), B_f is the final total larval dry biomass (g DM), and B_i is the initial total larval dry biomass (g DM, ~16.8 g).

$$\text{Substrate Mass Reduction (SMR, \%)} = \left[\frac{W_i - W_f}{W_i}\right] \times 100 \quad (5)$$

where W_f is the final residual frass dry mass (g DM). SMR quantifies total gravimetric mass loss resulting from larval ingestion, assimilation, and metabolic respiration.

$$\text{Biomass Conversion Efficiency (BCR, \%)} = \left[\frac{B_f - B_i}{W_i}\right] \times 100 \quad (6)$$

2.5. Statistical Analysis

Data were analyzed using IBM SPSS Statistics (Version 28.0; IBM Corp., Armonk, NY, USA). The experimental container was designated as the independent experimental unit. Normality of distributions and homogeneity of variances were confirmed using the Shapiro–Wilk and Levene's tests, respectively.

A preliminary two-way ANOVA incorporating Treatment as a fixed factor and Cycle as a blocking factor revealed no significant cycle effect or Treatment × Cycle interaction ($p > 0.05$ across all variables). Observations across the three cycles were therefore pooled ($n = 9$ replicate containers per treatment, total $N = 36$) and evaluated via one-way Analysis of Variance (ANOVA). Overall treatment effects are reported with degrees of freedom, F-values, exact p-values, and partial eta-squared (η_p^2) effect sizes. Treatment means were separated using Tukey's Honest Significant Difference (HSD) post hoc test at $\alpha = 0.05$. Results are presented as Mean ± Standard Deviation (SD).

3. Results

Dietary formulation significantly influenced all biological growth parameters, feed conversion efficiencies, and substrate mass reduction indices of *H. illucens* larvae ($p < 0.05$; Table 2). The statistical analysis confirmed substantial treatment effect sizes across all conversion metrics, with partial eta-squared (η_p^2) exceeding 0.84 for growth rate, FCR, and BCR, and reaching 0.974 for substrate mass reduction.

Table 2. Biological and bioconversion performance of *H. illucens* larvae reared on different sugar beet pulp-based substrate formulations.

Parameter	Control (100% Bran)	Option 1 (40% SBP)	Option 2 (40% SBP + *Trichoderma* sp.)	Option 3 (30% SBP + 10% Molasses)	Test Statistics (F, p, η_p^2)
Survival Rate (SR, %)	91.0 ± 3.8 ^{ab}	84.0 ± 8.8 ^{b}	85.0 ± 7.8 ^{b}	93.0 ± 1.8 ^{a}	$F_{3,32} = 4.52$, $p = 0.009$, $\eta_p^2 = 0.297$
Daily Growth Rate, wet (DLGR_wet, mg/d)	15.72 ± 0.39 ^{ab}	12.65 ± 0.76 ^{b}	12.83 ± 0.74 ^{b}	16.32 ± 0.83 ^{a}	$F_{3,32} = 66.86$, $p < 0.001$, $\eta_p^2 = 0.862$
Daily Growth Rate, dry (DLGR_dry, mg DM/d)	3.14 ± 0.08 ^{ab}	2.53 ± 0.15 ^{b}	2.57 ± 0.15 ^{b}	3.26 ± 0.17 ^{a}	$F_{3,32} = 66.88$, $p < 0.001$, $\eta_p^2 = 0.862$
Feed Conversion Ratio (FCR)	4.68 ± 0.11 ^{a}	5.87 ± 0.37 ^{b}	5.75 ± 0.33 ^{b}	4.52 ± 0.23 ^{a}	$F_{3,32} = 57.30$, $p < 0.001$, $\eta_p^2 = 0.843$
Substrate Mass Reduction (SMR, %)	71.30 ± 1.23 ^{b}	47.52 ± 2.67 ^{d}	53.04 ± 2.49 ^{c}	78.60 ± 2.15 ^{a}	$F_{3,32} = 401.03$, $p < 0.001$, $\eta_p^2 = 0.974$
Biomass Conversion Efficiency (BCR, %)	21.37 ± 0.53 ^{a}	17.04 ± 1.07 ^{b}	17.39 ± 1.00 ^{b}	22.12 ± 1.13 ^{a}	$F_{3,32} = 67.62$, $p < 0.001$, $\eta_p^2 = 0.864$

Note: Values represent Mean ± SD ($n = 9$ biological replicates pooled across three independent cycles, total $N = 36$). Means within a row sharing different superscript letters (a, b, c, d) are significantly different according to Tukey's HSD test ($p < 0.05$). All parameters except DLGR (wet) are calculated strictly on a dry matter (DM) basis.

3.1. Larval Survival and Growth Kinetics

Substrate formulation exerted a statistically significant effect on the survival rate of *H. illucens* larvae ($F_{3,32} = 4.52$, $p = 0.009$, $\eta_p^2 = 0.297$; Table 2). The highest larval survival was achieved in the co-diet formulation combining 30% SBP and 10% industrial molasses (Option 3: 93.0 ± 1.8%), maintaining exceptional consistency and minimal coefficient of variation (1.9%) across all three independent rearing cycles. In contrast, diets formulated with 40% raw SBP (Option 1: 84.0 ± 8.8%) and fungal-inoculated SBP (Option 2: 85.0 ± 7.8%) exhibited reduced survivability, differing significantly from Option 3 (Tukey's HSD, $p = 0.021$ and $p = 0.038$, respectively). However, survival rates in Option 1 and Option 2 were statistically comparable to the standard wheat bran Control (91.0 ± 3.8%; Tukey's HSD, $p = 0.089$ and $p = 0.142$, respectively). These results demonstrate that while the incorporation of 40% unsupplemented or fungal-inoculated SBP introduced physiological and ingestion

hurdles that lowered survival by 6.0 to 7.0 percentage points relative to the control, it did not cause acute or lethal toxicity. Furthermore, direct in situ inoculation with *Trichoderma* sp. (Option 2) failed to mitigate this physiological stress, yielding a survival rate that was statistically indistinguishable from unsupplemented SBP ($p = 0.978$).

Daily larval growth kinetics followed an identical response pattern, with overall dietary formulation exerting an exceptionally strong effect ($F_{3,32} = 66.86$, $p < 0.001$, $\eta_p^2 = 0.862$; Table 2). Diets containing 40% SBP without soluble carbohydrate balancing significantly depressed larval growth rates. Larvae in Option 1 and Option 2 achieved daily wet weight gains of only 12.65 ± 0.76 mg/d and 12.83 ± 0.74 mg/d, respectively, reflecting a 19.5% and 18.4% reduction compared to the Control (15.72 ± 0.39 mg/d; Tukey's HSD, $p < 0.001$). On a dry matter basis (DLGR_dry; $F_{3,32} = 66.88$, $p < 0.001$, $\eta_p^2 = 0.862$), individual somatic accumulation was similarly constrained at 2.53 ± 0.15 mg DM/d in Option 1 and 2.57 ± 0.15 mg DM/d in Option 2 versus 3.14 ± 0.08 mg DM/d in the Control ($p < 0.001$).

Conversely, the co-dietary modification in Option 3 (30% SBP + 10% molasses) completely restored larval growth performance, achieving an individual daily wet gain of 16.32 ± 0.83 mg/d (DLGR_dry: 3.26 ± 0.17 mg DM/d). This represented a statistically significant increase of 29.0% and 27.2% relative to Option 1 and Option 2, respectively ($p < 0.001$). Over the entire 18-day feeding trial, an individual larva in Option 3 attained a final average wet mass of approximately 303.8 mg (corresponding to ~61.5 mg DM), compared to only 237.7 mg wet (~48.3 mg DM) in Option 1. Although DLGR in Option 3 numerically surpassed the wheat bran Control by 3.8%, pairwise post hoc testing indicated that this difference was not statistically significant ($p = 0.187$). Therefore, partially replacing SBP with 10% molasses was fully sufficient to sustain larval growth rates on par with commercial cereal feed.

3.2. Feed Conversion Efficiency and Substrate Reduction

Feed conversion efficiency, evaluated via the Feed Conversion Ratio on a strict dry matter basis (FCR; dry substrate input divided by dry larval biomass gained), differed significantly among dietary treatments ($F_{3,32} = 57.30$, $p < 0.001$, $\eta_p^2 = 0.843$; Table 2). Substrates containing 40% SBP suffered from severely impaired conversion efficiency, requiring substantially greater dry substrate quantities to generate a unit of insect tissue. Specifically, Option 1 (FCR 5.87 ± 0.37) and Option 2 (FCR 5.75 ± 0.33) were statistically indistinguishable from each other ($p = 0.824$), but displayed significantly poorer conversion performance than the wheat bran Control (FCR 4.68 ± 0.11; Tukey's HSD, $p < 0.001$), representing an efficiency deficit of 25.4% and 22.9%, respectively. In Option 3, nutritional balancing with molasses and concomitant fiber dilution fully restored feeding efficiency, yielding an optimal FCR of 4.52 ± 0.23. This conversion ratio was significantly superior to both 40% SBP diets ($p < 0.001$) and statistically equivalent to the cereal Control ($p = 0.495$), demonstrating that the incorporation of molasses allowed larvae to allocate ingested nutrients toward somatic accretion with maximal bioenergetic efficiency.

Substrate Mass Reduction (SMR), which quantifies total gravimetric dry mass loss through larval ingestion, assimilation, and metabolic respiration, demonstrated clear, statistically distinct segregation across all four dietary regimes ($F_{3,32} = 401.03$, $p < 0.001$, $\eta_p^2 = 0.974$; Table 2). Unsupplemented SBP (Option 1) resulted in the poorest degradation efficiency, yielding an SMR of only 47.52 ± 2.67%, which left over 52.4% (566.8 g DM) of initial feed dry mass as recalcitrant, unconsumed frass. Inoculation with *Trichoderma* sp. (Option 2) produced a statistically significant enhancement in waste breakdown, increasing SMR to 53.04 ± 2.49% (Tukey's HSD, $p < 0.001$ vs. Option 1), representing a net reduction gain of 5.52 percentage points (59.6 g additional dry waste degraded per container). Despite

this improvement, waste processing in Option 2 remained substantially below the wheat bran Control (71.30 ± 1.23%; $p < 0.001$).

The most pronounced substrate reduction was recorded in Option 3 (SMR 78.60 ± 2.15%), which left only 231.1 g DM of residual frass per container. Option 3 degraded 31.08 and 25.56 percentage points more dry mass than Options 1 and 2, respectively ($p < 0.001$). Crucially, Option 3 also significantly outperformed the commercial 100% wheat bran Control by 7.30 percentage points ($p < 0.001$). This confirms that the synergistic combination of accessible soluble mono- and disaccharides and reduced structural fiber resistance acted as a potent behavioral and metabolic phagostimulant, driving larvae to ingest and process the substrate matrix to an unprecedented degree.

3.3. Biomass Conversion Efficiency (BCR)

Biomass Conversion Efficiency (BCR), defined as the percentage of initial dry feed successfully converted into harvested larval dry biomass, followed the bioenergetic trajectories observed for DLGR and FCR ($F_{3,32} = 67.62$, $p < 0.001$, $\eta_p^2 = 0.864$; Table 2). Larvae reared on 40% SBP diets achieved dry biomass conversion efficiencies of only 17.04 ± 1.07% (Option 1) and 17.39 ± 1.00% (Option 2), yielding total container biomass gains of approximately 184.0 g DM and 187.8 g DM, respectively. No significant difference was detected between the unsupplemented and fungal-inoculated treatments ($p = 0.812$), and both were significantly lower than the 21.37 ± 0.53% (230.8 g DM) recorded for the wheat bran Control ($p < 0.001$).

In sharp contrast, larvae in Option 3 achieved a peak conversion efficiency of 22.12 ± 1.13%, harvesting an average of 238.9 g of net larval dry biomass per container. Post hoc comparisons confirmed that the BCR in Option 3 was statistically equivalent to the Control ($p = 0.273$) while significantly outperforming Option 1 and Option 2 by 29.8% and 27.2%, respectively ($p < 0.001$). Across all biological, conversion, and degradation indices, the co-dietary strategy in Option 3 demonstrated that targeted carbohydrate supplementation combined with structural fiber alleviation completely eliminates the growth depressions and metabolic bottlenecks associated with raw sugar beet pulp bioconversion.

4. Discussion

The effective valorization of agro-industrial side-streams via insect bioconversion depends on addressing substrate-specific mechanical, nutritional, and enzymatic constraints. Sugar beet pulp contains a dense cell-wall polysaccharide network (pectin, cellulose, hemicellulose) combined with moderate crude protein content (7–10% DM) [12–14]. Our results indicate that unsupplemented inclusion of SBP at 40% DM reduces growth rate, feed conversion efficiency, and substrate reduction. However, a co-dietary strategy combining 30% SBP with 10% molasses substantially improved these metrics, matching or exceeding the standard wheat bran control.

4.1. Nutritional and Structural Factors in Sugar Beet Pulp Bioconversion

The lower growth rates (12.65 mg/d wet) and biomass conversion efficiency (17.04%) in Option 1 reflect the compositional characteristics of raw SBP. Replacing 40% of wheat bran (which contains ~15.8% crude protein) with SBP (~9.1% crude protein) dilutes dietary nitrogen [22]. Dietary protein availability is a primary factor influencing somatic tissue synthesis in *H. illucens* [15,28]. When dietary protein is low, larvae often require greater substrate consumption to meet physiological amino acid requirements, contributing to higher FCR values (5.87) [25,32].

In addition, SBP is characterized by high pectin content (~24% DM) with substantial water-holding and swelling capacities [12,14]. In hydrated substrates, pectin can form

viscous gels that alter physical texture. Because dipteran larvae rely on physical churning and peristaltic processing of ingested mash, high substrate viscosity can impede feed ingestion and slow the diffusion of endogenous digestive enzymes [21,22,24]. These physical properties, alongside the absence of endogenous cellulase machinery in *H. illucens*, likely account for the lower substrate mass reduction observed in Option 1 (SMR 47.52%).

4.2. Response to In Situ Inoculation with Trichoderma sp.

Biological fungal inoculation is often evaluated for softening lignocellulosic materials [26,27]. In our trial, in situ addition of *Trichoderma* sp. conidia (Option 2) resulted in a modest increase in substrate mass reduction (53.04% vs. 47.52% in Option 1; $p < 0.001$), suggesting that fungal activity provided minor degradation of the substrate matrix.

However, in situ fungal inoculation did not improve larval survival (85.0%), daily growth rate (12.83 mg/d wet), FCR (5.75), or BCR (17.39%) relative to Option 1. This outcome indicates that direct co-inoculation of fungal spores without an external pre-incubation phase is insufficient to enhance larval growth. Because larvae actively feed from day 1, the fungus lacks the residence time required to establish extensive mycelial networks and secrete high enzyme titers before the substrate is consumed or disturbed. Furthermore, fungal inoculation does not alter the baseline protein-to-carbohydrate balance of the substrate [15,25]. Consequently, if fungal treatment is to be applied to SBP, decoupled solid-state pre-fermentation prior to larval introduction warrants investigation rather than direct in situ inoculation [23,26,27].

4.3. Combined Mechanisms of Nutritional Balancing in Option 3

The bioconversion metrics recorded for Option 3 (DLGR_wet 16.32 mg/d, FCR 4.52, SMR 78.60%, BCR 22.12%) reflect the combined modification of reducing SBP content from 40% to 30% while incorporating 10% molasses. This co-dietary adjustment addresses both physical and nutritional limitations:

- Metabolic Energy Availability: Molasses supplies an abundant pool of readily fermentable mono- and disaccharides (sucrose, glucose, fructose) [12,28]. Readily accessible carbohydrates provide direct energy for larval metabolism, reducing the need to catabolize dietary amino acids for basal maintenance and allowing protein to be partitioned toward tissue growth [16,28].
- Substrate Rheology and Gut Dynamics: Reducing SBP from 40% to 30% decreased total structural fiber and pectin content, lowering substrate viscosity and physical resistance. Concurrently, soluble sugars can serve as substrates for commensal gut and feed-associated microflora, which may release secondary exogenous enzymes in the digestive tract that assist in breaking down complex carbohydrates [15,25,36].

These combined effects enabled Option 3 to achieve an SMR of 78.60%, significantly higher than the 100% wheat bran Control (71.30%), while achieving comparable biomass conversion (BCR 22.12% vs. 21.37%).

4.4. Circular Bioeconomy Context

In major agricultural regions, sugar beet processing co-locates wet pulp and molasses. Integrating insect bioconversion facilities with existing sugar refining infrastructure represents a potential circular valorization pathway [1,3,35]. Utilizing fresh pulp on-site could circumvent fuel requirements for thermal drying and reduce long-distance transport logistics [2,4–7].

Moreover, biological upcycling of agro-industrial by-products via insects complements other emerging biorefinery concepts. While microbial acidogenic fermentation can convert food processing streams into volatile fatty acids and biochemicals [8], and integrated systems can route residues into microbial polyhydroxyalkanoates (PHAs) [9], insect rearing

directly yields larval biomass suitable for downstream protein and lipid recovery [10,17,18]. Converting wet organic side-streams through controlled biological systems also avoids open disposal pathways that can generate diffuse methane and nitrous oxide emissions [2,36,37].

4.5. Limitations and Future Research Directions

Several methodological aspects of this study should be recognized:

- Confounded Dietary Factors: Option 3 combined a 10% addition of molasses with a 10% reduction in SBP content. Therefore, the observed improvements reflect the combined effect of soluble sugar supplementation and fiber dilution. Future studies employing multi-factorial response surface designs are recommended to isolate the individual contributions of sugar concentration, protein supplementation, and fiber levels.
- Biological Pre-treatment Protocols: We evaluated only direct in situ fungal inoculation. Dedicated multi-day solid-state pre-fermentation protocols with *Trichoderma* sp. or yeast strains prior to larval stocking should be explored to determine whether decoupled pre-digestion can enhance fiber utilization [13,26,27].
- Harvesting Protocol: Larvae were harvested without a 24 h fasting period, following commercial whole-larva processing conventions. While this reflects industrial practice, gut contents may influence final biomass composition.
- Biochemical Characterization: Substrates, frass, and larvae were evaluated gravimetrically on a dry matter mass-balance basis to model conversion kinetics and mass reduction. Detailed proximate composition (crude protein, amino acids, crude fat, fatty acid profiles, and fiber fractions) of incoming feeds and harvested materials was allocated to a companion study.

5. Conclusions

Unsupplemented sugar beet pulp incorporated at 40% DM reduces *H. illucens* growth kinetics and feed conversion efficiency (DLGR_wet 12.65 mg/d, FCR 5.87, BCR 17.04%) due to structural fiber constraints and dietary protein dilution relative to standard wheat bran. Direct in situ inoculation of SBP-based diets with *Trichoderma* sp. without prior incubation produced a minor increase in substrate mass reduction (SMR 53.04%) but did not improve larval growth, survival, or feed conversion. A co-dietary formulation combining 30% SBP and 10% molasses (Option 3) substantially improved bioconversion performance, achieving high survival (93.0%), lowest FCR (4.52), peak substrate reduction (78.60%), and a biomass conversion efficiency of 22.12%, matching or exceeding the standard wheat bran Control. These results demonstrate that combining soluble carbohydrate supplementation with structural fiber reduction is an effective formulation approach for valorizing high-fiber agro-industrial co-products in commercial black soldier fly bioconversion systems.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Acid Detergent Fiber
BCR	Biomass Conversion Efficiency (%)
BSF	Black Soldier Fly
CFU	Colony-Forming Units
DLGR	Daily Larval Growth Rate (mg/d)
DM	Dry Matter
FCR	Feed Conversion Ratio
HSD	Honest Significant Difference
NDF	Neutral Detergent Fiber
PHA	Polyhydroxyalkanoate
SBP	Sugar Beet Pulp
SD	Standard Deviation
SDG	Sustainable Development Goals
SMR	Substrate Mass Reduction (%)
SR	Survival Rate (%)

References

1. van Huis, A.; Oonincx, D.G.A.B. The environmental sustainability of insects as food and feed. A review. *Agron. Sustain. Dev.* **2017**, *37*, 43. [CrossRef]
2. Mertenat, A.; Diener, S.; Zurbrügg, C. Black soldier fly biowaste treatment—Assessment of global warming potential. *Waste Manag.* **2019**, *84*, 173–181. [CrossRef] [PubMed]
3. Čičková, H.; Newton, G.L.; Lacy, R.C.; Kozánek, M. The use of fly larvae for organic waste treatment. *Waste Manag.* **2015**, *35*, 68–80. [CrossRef] [PubMed]
4. Cadinu, L.A.; Barra, P.; Torre, F.; Delogu, F.; Madau, F.A. Insect Rearing: Potential, Challenges, and Circularity. *Sustainability* **2020**, *12*, 4567. [CrossRef]
5. Ghirisan Miclaus, A.; Simion, D.; Coța, C.; Nagy, E.M.; Zoltan, G.; Miclaus, V. Modelling of the Sugar Beet Pulp Drying Process. *Stud. Univ. Babes-Bolyai Chem.* **2020**, *65*, 21–28. [CrossRef]
6. Jiang, G.; Zhang, Y.; Luo, D.; Zhu, S.; Wang, Y.; Li, W. Drying Model and Mechanism of Sugar Beet Pulp Based on Its Crosslinking with Ca^{2+} and Cu^{2+}. *Foods* **2025**, *14*, 3362. [CrossRef] [PubMed]
7. Garcia Gonzalez, M.N.; Björnsson, L. Life cycle assessment of the production of beet sugar and its by-products. *J. Clean. Prod.* **2022**, *346*, 131211. [CrossRef]
8. Marchetti, A.; Salvatori, G.; Astolfi, M.L.; Fabiani, M.; Fradinho, J.; Reis, M.A.M.; Gianico, A.; Bolzonella, D.; Villano, M. Evaluation of the acidogenic fermentation potential of food industry by-products. *Biochem. Eng. J.* **2023**, *199*, 109029. [CrossRef]
9. Salvatori, G.; Marchetti, A.; Russo, A.M.; Rodriguez, J.; Scerbacov, V.; Fianelli, F.; Alfano, S.; Crognale, S.; Massimi, A.; Rossetti, S.; et al. Pilot-Scale Acidogenic Fermentation of Reground Pasta Byproduct for Polyhydroxyalkanoate Production with Mixed Microbial Cultures. *ACS Sustain. Chem. Eng.* **2025**, *13*, 3024–3035. [CrossRef] [PubMed]
10. Surendra, K.C.; Tomberlin, J.K.; van Huis, A.; Cammack, J.A.; Heckmann, L.-H.L.; Khanal, S.K. Rethinking organic wastes bioconversion: Evaluating the potential of the black soldier fly (*Hermetia illucens* (L.)) (Diptera: Stratiomyidae) (BSF). *Waste Manag.* **2020**, *117*, 58–80. [CrossRef] [PubMed]
11. Eggink, K.M.; Lund, I.; Pedersen, P.B.; Hansen, B.W.; Dalsgaard, J. Biowaste and by-products as rearing substrates for black soldier fly (*Hermetia illucens*) larvae: Effects on larval body composition and performance. *PLoS ONE* **2022**, *17*, e0275213. [CrossRef] [PubMed]
12. Bouassida, M.; Fourati, M.; Zouari, R.; Ellouze-Chaabouni, S.; Ghribi, D. Sugar beet molasses bioconversion into biosurfactant: Optimization and comparison with other carbon sources. *Biomass Convers. Biorefin.* **2024**, *14*, 4679–4689. [CrossRef]
13. Gaizauskaite, Z.; Zadeike, D. Valorisation of Sugar Beet Processing Waste for Enhanced Production of Fungal Biomass as a Sustainable Alternative Protein Source. *Appl. Sci.* **2025**, *15*, 13165. [CrossRef]
14. Usmani, Z.; Sharma, M.; Diwan, D.; Tripathi, M.; Whale, E.; Jayakody, L.N.; Moreau, B.; Thakur, V.K.; Tuohy, M.; Gupta, V.K. Valorization of sugar beet pulp to value-added products: A review. *Bioresour. Technol.* **2022**, *346*, 126580. [CrossRef] [PubMed]

15. Zhang, Y.; Huang, G.; Wei, X.; Zhang, Y.; Chen, S.; Sui, Z.; Huang, D.; Xiao, J. Bioconversion of black soldier fly larvae on agricultural by-products: Study on growth, nutrition, physicochemical properties, metabolic profiling, and larvae-substrate component correlations. *J. Clean. Prod.* **2025**, *521*, 146250. [CrossRef]
16. Lu, S.; Taethaisong, N.; Meethip, W.; Surakhunthod, J.; Sinpru, P.; Sroichak, T.; Archa, P.; Thip-uten, R.; Cherdthong, A.; Cai, Y.; et al. Nutritional Composition of Black Soldier Fly Larvae (*Hermetia illucens* L.) and Its Potential Uses as Alternative Protein Sources in Animal Diets: A Review. *Insects* **2022**, *13*, 831. [CrossRef] [PubMed]
17. Belghit, I.; Liland, N.S.; Gjesdal, P.; Biancarosa, I.; Menchetti, E.; Li, Y.; Waagbø, R.; Krogdahl, Å.; Lock, E.-J. Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (Salmo salar). *Aquaculture* **2019**, *503*, 609–619. [CrossRef]
18. Cullere, M.; Tasoniero, G.; Giaccone, V.; Miotti-Scapin, R.; Claeys, E.; De Smet, S.; Dalle Zotte, A. Black soldier fly as a dietary protein source for broiler quails: Apparent digestibility, growth performance and carcass traits. *Animal* **2016**, *10*, 1923–1930. [CrossRef] [PubMed]
19. Stubelj, M.; Gleščič, E.; Žvanut, B.; Širok, K. Factors influencing the acceptance of alternative protein sources. *Appetite* **2025**, *209*, 107976. [CrossRef] [PubMed]
20. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; UN Publishing: New York, NY, USA, 2015; pp. 14–26.
21. Asiry, K.A.; Attia, Y.A.; Bovera, F.; Addeo, N.F.; Al-Ghamdi, A.G.; Alqurashi, S.I.; Alhotan, R.A.; Al-Fiqi, A.; Ibrahim, O.H.; Alrefaei, M.S. Substrate and stage effects on growth, composition, frass traits, and economic efficiency in black soldier fly (*Hermetia illucens*). *Bull. Entomol. Res.* **2026**, *116*, 355–370. [CrossRef] [PubMed]
22. Meneguz, M.; Schiavone, A.; Gai, F.; Dama, A.; Lussiana, C.; Renna, M.; Gasco, L. Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae. *J. Sci. Food Agric.* **2018**, *98*, 5776–5784. [CrossRef] [PubMed]
23. Peguero, D.A.; Gold, M.; Vandeweyer, D.; Zurbrügg, C.; Mathys, A. A review of pretreatment methods to improve agri-food waste bioconversion by black soldier fly larvae. *Front. Sustain. Food Syst.* **2022**, *5*, 745894. [CrossRef]
24. Palma, L.; Fernandez-Bayo, J.; Niemeier, D.; Pitesky, M.; VanderGheynst, J.S. Managing high fiber food waste for the cultivation of black soldier fly larvae. *npj Sci. Food* **2019**, *3*, 15. [CrossRef] [PubMed]
25. Gold, M.; Cassar, C.M.; Zurbrügg, C.; Kreuzer, M.; Boulos, S.; Diener, S.; Mathys, A. Biowaste treatment with black soldier fly larvae: Increasing performance through the formulation of biowastes based on protein and carbohydrates. *Waste Manag.* **2020**, *102*, 319–329. [CrossRef] [PubMed]
26. Isibika, A.; Vinnerås, B.; Kibazohi, O.; Zurbrügg, C.; Lalander, C. Pre-treatment of banana peel to improve composting by black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae) larvae. *Waste Manag.* **2019**, *100*, 151–160. [CrossRef] [PubMed]
27. Somroo, A.A.; ur Rehman, K.; Zheng, L.; Cai, M.; Xiao, X.; Hu, S.; Mathys, A.; Gold, M.; Yu, Z.; Zhang, J. Influence of Lactobacillus buchneri on soybean curd residue co-conversion by black soldier fly larvae (*Hermetia illucens*) for food and feedstock production. *Waste Manag.* **2019**, *86*, 114–122. [CrossRef] [PubMed]
28. Mohammad, S.F.; Shah, A.A.; Wanapat, M.; El-Mogy, M.M. Utilizing Insects to Convert Waste Into Nutrients for Sustainable Feed and Food Production. *Entomol. Res.* **2026**, *56*, e70105. [CrossRef]
29. Bekker, N.S.; Heidelbach, S.; Vestergaard, S.Z.; Nielsen, M.E.; Riisgaard-Jensen, M.; Zeuner, E.J.; Bahrndorff, S.; Eriksen, N.T. Impact of substrate moisture content on growth and metabolic performance of black soldier fly larvae. *Waste Manag.* **2021**, *127*, 73–79. [CrossRef] [PubMed]
30. Diener, S.; Zurbrügg, C.; Tockner, K. Conversion of organic material by black soldier fly larvae: Establishing optimal feeding rates. *Waste Manag. Res.* **2009**, *27*, 603–610. [CrossRef] [PubMed]
31. Bosch, G.; van Zanten, H.H.E.; Zamprogna, A.; Veenenbos, M.; Meijer, N.P.; van der Fels-Klerx, H.J.; van Loon, J.J.A. Conversion of organic resources by black soldier fly larvae: Legislation, efficiency and environmental impact. *J. Clean. Prod.* **2019**, *222*, 355–363. [CrossRef]
32. Schiavone, A.; De Marco, M.; Martínez, S.; Dabbou, S.; Renna, M.; Madrid, J.; Hernandez, F.; Rotolo, L.; Costa, P.; Gai, F.; et al. Nutritional value of a partially defatted and a highly defatted black soldier fly larvae (*Hermetia illucens* L.) meal for broiler chickens: Apparent nutrient digestibility, apparent metabolizable energy and apparent ileal amino acid digestibility. *J. Anim. Sci. Biotechnol.* **2017**, *8*, 51. [CrossRef] [PubMed]
33. Bava, L.; Jucker, C.; Gislon, G.; Lupi, D.; Savoldelli, S.; Zucali, M.; Colombini, S. Rearing of *Hermetia illucens* on Different Organic By-Products: Influence on Growth, Waste Reduction, and Environmental Impact. *Animals* **2019**, *9*, 289. [CrossRef] [PubMed]
34. Gao, Z.; Wang, W.; Lu, X.; Zhu, F.; Liu, W.; Wang, X.; Lei, C. Bioconversion performance and life table of black soldier fly (*Hermetia illucens*) on fermented maize straw. *J. Clean. Prod.* **2019**, *230*, 974–980. [CrossRef]
35. Lopes, I.G.; Yong, W.T.L.; Lalander, C. Frass derived from black soldier fly larvae treatment of biodegradable wastes. A critical review and future perspectives. *Waste Manag.* **2022**, *142*, 65–76. [CrossRef] [PubMed]

36. Parodi, A.; De Boer, I.J.M.; Gerrits, W.J.J.; Van Loon, J.J.A.; Heetkamp, M.J.W.; Van Schelt, J.; Bolhuis, J.E.; Van Zanten, H.H.E. Bioconversion efficiencies, greenhouse gas and ammonia emissions during black soldier fly rearing—A mass balance approach. *J. Clean. Prod.* **2020**, *271*, 122488. [CrossRef]
37. Van Huis, A.; Oonincx, D.G.A.B.; Rojo, S.; Tomberlin, J.K. Insects as feed: House fly or black soldier fly? *J. Insects Food Feed.* **2020**, *6*, 221–229. [CrossRef]

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