DOI: 10.33003/chemclass-2026-1002/03 June 2026; Vol. 10 Issue 2; 10-22

ChemClass Journal
Publication of the Chemical Society of Nigeria, Zaria Chapter
Journal homepage: https://chemclassjournal.com.ng
e-ISSN: 3092-8214; p-ISSN: 3092-8206

Review Article

Substrate composition effects on black soldier fly larvae growth and bioconversion: A meta-analysis review

Alexander O. Ogabidu*[,1], Olanipekun O. Idowu[1], Sunday A. Abe[1], Ibrahim Abdulwaliyu[1], Dawaki S. Idris[1], Judy A. Adudu[1], Evelyn H. Odeke[1], Christiana A. Aluku[1], Nuhu N. Aliyu[1], Aishat G. Haruna[1], Alheri C. John[1]

[1] Biochemical and Microbiology Division, Scientific and Industrial Research Department, National Research Institute for Chemical Technology, Zaria, Kaduna State, Nigeria

OPEN ACCESS

***Corresponding Author**
Ogabidu A.O.
ogabiduokpokwu1@gmail.com
Phone: +234-906-795-3564
ORCID: 0009-0000-3984-4188

Article History
Received: April 11, 2026
Reviewed: April 27, 2026
Revised: April 30, 2026
Accepted: May 06, 2026
Published: June 30, 2026

Citation
Ogabidu A.O., Idowu O.O., Abe S.A., Abdulwaliyu I., Idris D.I.., Adudu J.A., Odeke E.H., Aluku C.A., Aliyu N.N., Haruna A.G., John A.C. (2026). Substrate composition effects on black soldier fly larvae growth and bioconversion: A meta analysis review. *ChemClass Journal,* 10(2), 10-22 DOI: 10.33003/chemclass-2026-1002/03

Copyright © 2026 Ogabidu A.O. et al. Published by CSN Zaria Chapter. This is an open-access article distributed under the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

ABSTRACT

As organic waste production rises, sustainable bioconversion technologies that adhere to the circular economy's tenets are needed. The larva of the Black Soldier Fly (*Hermetia illucens*, BSFL) has become an important organism for turning various organic wastes into nutrient-dense frass and biomass that is high in protein. Nonetheless, the substrate composition has a significant impact on this process's efficiency. 131 international empirical research published between 2015 and 2026 are compiled in this systematic review and meta-analysis to quantitatively evaluate the effects of substrate properties on BSFL growth and bioconversion efficiency. The results indicate that crude protein content and carbon-to-nitrogen (C/N) ratio are the main factors influencing larval biomass yield and feed conversion efficiency, with 18–22% protein and a C/N ratio of 20–25:1 producing the best results. Multivariate modelling reveals important relationships between important parameters and emphasizes the complementary advantages of combining substrate pre-treatments, especially microbial inoculation and physical size reduction. Significant adaptability may be shown in the larvae's dietary makeup, which closely reflects substrate characteristics. This study demonstrates that BSFL bioconversion is governed by interacting substrate factors rather than single traits and provides a predictive framework for optimizing substrates for scalable and sustainable waste management.

Keywords: Bioconversion efficiency; Black soldier fly larvae; Circular bioeconomy; Organic waste valorisation; Substrate optimization

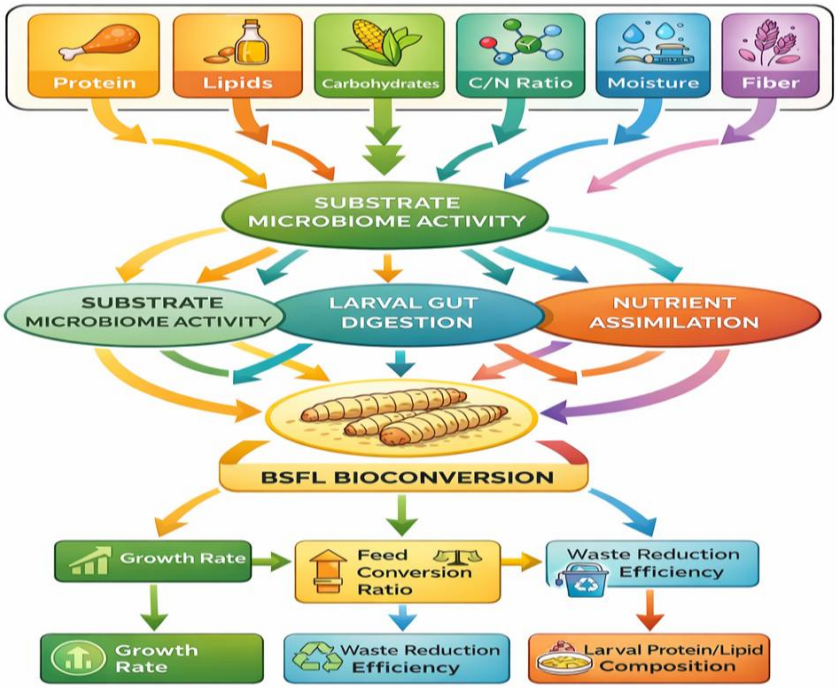
Introduction

Global organic waste generation has increased at an unprecedented rate due to the world's population growth, urbanization, and industrialization. Global production of over 1.3 billion tonnes of food waste and roughly 1.5 billion tonnes of agricultural residues each year poses serious environmental, economic, and social problems [1]–[5]. In addition to causing nutrient loss, soil and water contamination, and greenhouse gas emissions, especially methane, conventional waste management techniques like landfilling and incineration are becoming more widely acknowledged as unsustainable [3], [6], [7]. The circular economy (CE) framework, which rethinks waste as a resource and encourages closed-loop systems meant to lessen environmental degradation while maintaining economic growth, has emerged as a transformative paradigm in response [8]–[10]. In this circular framework, insect-based bioconversion has become more popular as a scalable and effective way to value organic waste. The Black Soldier Fly (*Hermetia illucens*), one of the species under investigation, has emerged as one of the most promising biological agents for turning low-value organic residues into high-value products [1], [11]–[13]. The larval stage, known as Black Soldier Fly larvae (BSFL), has an amazing ability to quickly consume and break down a variety of organic substrates, such as animal manures, agro-industrial byproducts, municipal food waste, and agricultural residues.

The two main products of this process are frass and nutrient-dense larval biomass. The larval biomass is a good substitute for traditional feed ingredients like fishmeal and soybean meal because it usually contains 35–50% crude protein and 20–40% lipids on a dry matter basis [14]–[16]. With proven agronomic value, the leftover frass is used as an organic fertilizer that is high in nutrients [17]–[19]. As a result, BSFL systems closely correspond with several SDGs of the United Nations [20]–[22].

Despite these benefits, substrate composition has a significant impact on the efficiency and viability of BSFL bioconversion systems. The substrate's chemical and structural properties directly affect growth performance and conversion efficiency because it serves as the only source of nutrients and the physical medium for larval development [23]–[25]. The characteristics of the substrate have a significant impact on key performance metrics, such as larval development time, survival rate, biomass yield, feed conversion ratio (FCR), and waste reduction efficiency (WRE). The balance of macronutrients is especially crucial. While carbohydrate-dominant substrates may increase lipid deposition, protein-rich substrates typically encourage faster growth and higher protein accretion [25]–[29]. Nitrogen availability and microbial dynamics are largely regulated by the carbon-to-nitrogen (C/N) ratio, with optimal larval performance typically reported within a range of roughly 15:1 to 25:1 [30], [31]. Variations from this range may lead to ammonia toxicity in the case of excessive nitrogen or nutrient limitation in the case of excessive carbon. Another important aspect is moisture content, and in the majority of studies, it is determined that the range of 60-70% is optimal; less or more may lead to low activity in feeding or anaerobic conditions [32]–[36]. Moreover, lignocellulosic substrates (cellulose and lignin) can inhibit digestion and decrease bioconversion due to the low endogenous cellulolytic activity of the larva [2], [30]. Microbial community dynamics significantly impact the processes of substrate degradation and nutrient assimilation. Indigenous microbiota may facilitate nutrient mineralization, inhibit pathogenic organisms, and influence the health of larval gastrointestinal systems through pre-digestive mechanisms [37]–[40]. In order to enhance substrate appropriateness and mitigate variability in performance outcomes, a myriad of pre-treatment methodologies has been explored. These methodologies encompass physical techniques such as grinding and drying, chemical interventions such as alkaline hydrolysis, and biological strategies such as fermentation and microbial inoculation involving species such as *Bacillus* and *Lactobacillus* [39], [41]–[43].

In the last decade, investigations into the optimization of substrates for Black Soldier Fly larvae (BSFL) have significantly proliferated, yielding a considerable array of empirical studies that scrutinize individual substrates or simplistic mixtures [44]–[48]. While numerous narrative reviews have qualitatively delineated the effects of substrates [49]–[52], the existing literature is notably fragmented, and conclusions frequently exhibit inconsistencies attributable to methodological variations and substrate heterogeneity. A thorough quantitative synthesis that amalgamates these findings and elucidates consistent patterns across diverse studies is yet to be realized. Consequently, the principal objective of this investigation is to execute a systematic review and meta-analysis to quantitatively ascertain the manner in which substrate composition affects the growth and bioconversion efficacy of Black Soldier Fly larvae, thereby pinpointing optimal parameter ranges that can inform evidence-based substrate formulation for scalable and effective BSFL systems.



Scheme 1. Conceptual Framework of Key Substrate Parameters Influencing BSFL Bioconversion

Methodology

Systematic Literature Search and Screening Protocol

Search strategy

A comprehensive, systematic literature search was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [58]. The search was executed across three major electronic databases: Scopus, Web of Science Core Collection, and PubMed/Medline. To capture the evolution of the field, the search period was set from January 2015 to January 2026, ensuring inclusion of foundational studies and the most recent advancements. The search strategy employed a combination of controlled vocabulary such as MeSH terms in PubMed and free-text keywords tailored to each database. The core search string was structured around three conceptual blocks: *Hermetia illucens* or black soldier fly or black soldier fly larvae or BSFL. The exposition includes substrate or diet or feed or organic waste or food waste or manure or agricultural residue or agro-industrial by-product growth or biomass yield or feed conversion ratio or FCR or development time or waste reduction or nutrient composition or protein or lipid or bioconversion efficiency. Sensitivity was increased by using truncation symbols (*) and boolean operators (AND, OR) [56], [57].

Supplementary search and study identification

To minimize publication bias and ensure comprehensiveness, supplementary searches were performed. Citation tracking, both forward and backward. All included research reference lists and pertinent review papers were examined. Important works were also tracked for forward citations using Google Scholar's "cited by" feature. Grey literature: to find pertinent unpublished data, conference proceedings from significant entomology and waste management societies as well as preprint servers (bioRxiv, ResearchSquare) were examined. Consultation with experts: to find any ongoing or unpublished research that fit the inclusion criteria, corresponding authors of five or more pertinent publications were sought out.

Study screening and selection

Duplicate results were eliminated once the search results were entered into Zotero 6.0, a reference management program. Using the web-based application Rayyan.ai, two independent reviewers (Reviewer A and B) reviewed the remaining records in two stages [59]. Screening of title and abstract: records were examined in light of initial inclusion or exclusion standards. Disagreements were settled by discussion or by a third senior reviewer. Full-text evaluation: every study that might be eligible had its complete text obtained and carefully evaluated in light of the formal eligibility requirements. The PRISMA 2020 flow diagram covers the selection procedure and exclusion criteria in full (Figure 1).

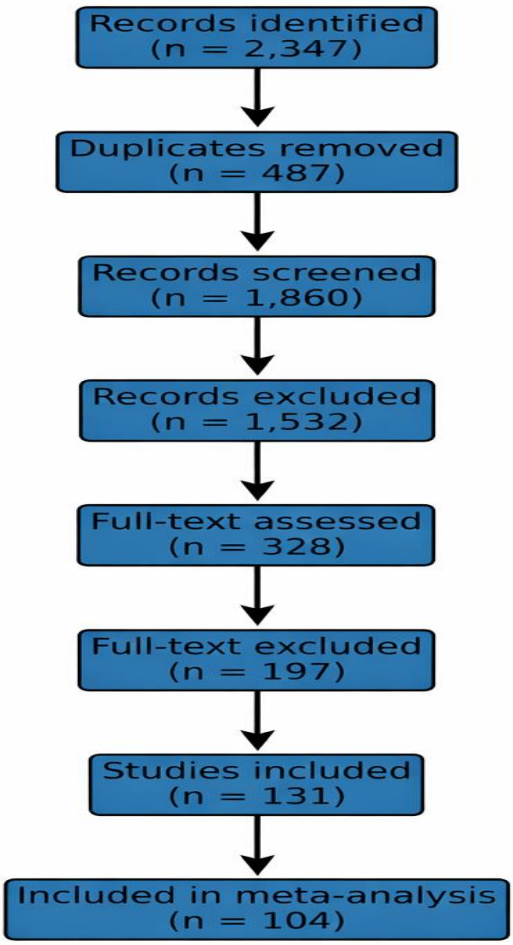


Figure 1. PRISMA 2020 Flow Diagram of the Study

Eligibility Criteria

Inclusion criteria

Studies were accepted if they satisfied each of the following requirements: Population: *Hermetia illucens* larvae raised in laboratories or on pilot projects (almost all instars, but mostly the last instar mentioned). Exposure/intervention: Larvae raised on one or more distinct organic substrates or waste streams (e.g., described manure, defined agricultural residue, unique food waste). Research that presents quantitative information on a minimum of two essential substrate properties (e.g., moisture percentage, C/N ratio, fibre content, and crude protein percentage). Comparator: Either a control substrate (like regular chicken feed) or a comparison of several substrate treatments within the same study. Outcomes: Quantitative information provided on at least two of the major performance measures: development period (days), biomass gain (mg/day), final larval weight (mg/larva), larval yield (g/kg substrate); Feed Conversion Ratio (FCR: dry substrate consumed/dry larval biomass produced), Waste Reduction Efficiency (WRE: percentage dry matter reduction), Bioconversion Efficiency (BE: percentage); larval crude protein content (% DM), larval lipid content (% DM), key amino acid or fatty acid profiles. Study Design: Primary empirical study including pilot-scale trials, controlled

laboratory tests, and studies comparing rearing methods. Report of the number of independent replicates per treatment ($n \geqslant 3$) and measures of variance (standard deviation, standard error, confidence intervals) from the data supplied.

Exclusion criteria

Any one of the following factors led to exclusion: Language: Published in a language other than English. Study Type: Review articles, editorials, opinion pieces, modelling studies without primary data, life cycle assessments (LCA) without corresponding empirical rearing data. Inadequate Data: Research that only presents qualitative results, does not include necessary quantitative metrics or measures of variance, where data cannot be estimated or extracted from tables, figures, or text (even after contacting authors). Non-Standard Rearing: Research that did not include data on larval performance and only examined adult flies, pupae, or eggs. Contaminated or Modified Larvae: Studies using genetically modified larvae or larvae exposed to non dietary treatments, e.g., heavy metal toxicity studies where metal is added independently of the substrate.

Data Extraction and Management

In Microsoft Excel, a pre-piloted, standardized data extraction form was created. Two independent reviewers retrieved the following information from each included study: Bibliographic Details: DOI, journal, year of publication, and author(s). Study *Characteristics*: Country of origin, experiment scale (lab/pilot), rearing time, larval density, initial larval weight/age; environmental parameters: temperature (°C), relative humidity (%), photoperiod, aeration technique. Characterization of the Substrate: Type and source (e.g., mixed food waste, brewers' spent grain, poultry manure). Approximate composition: moisture (%), crude protein (%), crude lipid (%), ash (%), carbohydrate (by difference). Fiber analysis: Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF), lignin (if indicated). C/N ratio, pH. Pre-treatment: method (none, grinding, drying, fermentation, microbial inoculation, enzymatic, chemical), specific agents used, duration.

Outcome data: For continuous variables: sample size (n), mean, standard deviation (SD). If SD was not provided, it was computed from p-values, standard error (SE), or confidence intervals (CI) using established methods [60]. For dichotomous variables: total sample size and number of occurrences (e.g., survival rate >80%).

Risk of Bias Assessment

An adaptation of SYRCLE's risk of bias tool for animal studies [61] was used by two reviewers to independently evaluate methodological quality and risk of bias of individual studies in insect rearing experiments. Assessed domains included: randomization of experimental units, baseline similarity between batches of larvae, blinding of outcome assessors and caregivers, incomplete outcome data (attrition bias), selective reporting, and other sources of bias (e.g., funding conflicts, unrealistic rearing conditions). Each domain was graded as low, high, or unclear. This judgment informed sensitivity analyses in the meta-analysis.

Meta-Analytical Strategy

Calculation of effect sizes

The primary effect size for continuous outcomes comparing two substrate treatments (e.g., Treatment A vs. Control B) was the standardized mean difference (Hedges' g). Hedges' g is expressed as small (0.2), medium (0.5), and large (0.8) and incorporates a correction for small sample bias [62]. The formula was g = (Mean$_1$ – Mean$_2$) / S_{pooled} * J, where J is the correction factor and S_{pooled} is the pooled standard deviation. For studies with multiple treatment groups compared to a single control, the control group sample size was divided to avoid unit-of-analysis error [60].

Statistical models and heterogeneity

All meta-analyses were performed using R software (v4.3.0) and the *metafor* package (v4.0). A random-effects model with the restricted maximum-likelihood (REML) estimator was used for primary analyses because we expected significant variability due to differences in substrates, rearing techniques, and environmental conditions across studies. Heterogeneity was quantified using the I^2 statistic (25%, 50%, and 75% indicating low, moderate, and high heterogeneity, respectively). Between-study variation was reported as τ^2.

Multivariate and subgroup analyses

Several advanced analytical techniques were used to model interacting parameters. Multilevel meta regression models were built using continuous and categorical predictors (substrate protein percentage, C/N ratio, moisture percentage, pre-treatment type) to predict effect sizes for outcomes such as FCR and biomass yield. Interaction terms (e.g., Protein × C/N) were included to detect synergies or antagonisms. Pre-planned subgroup analyses (meta-ANOVA) were conducted to explore sources of heterogeneity: substrate categories (animal dung, food waste, agricultural residue, agro-industrial by-product, mixed/co-digested); pre-treatment (none, physical, microbial, chemical/enzymatic); C/N ratio (optimal 15-30:1, high >30:1, low <15:1). Mixed-effects meta-ANOVA models were used. For dose-response and non-linear modelling, restricted cubic spline meta-regression models were fitted for continuous predictors (e.g., dietary protein level).

Assessment of publication bias and sensitivity analyses

Publication Bias: Asymmetry was visually examined in funnel plots. For meta-analyses with at least 10 studies, Egger's regression test was used [63]. Sensitivity analyses: Influence analysis (iterative removal of one study at a time), risk-of-bias analysis (comparing pooled estimates from low-, high-, and unclear-risk studies), model selection (fixed-effect vs. random-effects), and data imputation (handling of missing SD) were performed.

Certainty of evidence

The Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach, modified for pre-clinical animal research, was used to assess overall certainty (quality) of evidence for each major outcome [64]. Evidence was downgraded for risk of bias, inconsistency (high heterogeneity), indirectness, imprecision, and publication bias.

Results

Study Selection and Characteristics

The initial systematic search across PubMed, Web of Science, and Scopus yielded 2,347 records (Figure 1). After removing 487 duplicates, 1,860 records were screened by title and abstract; 1,532 were excluded as irrelevant. The remaining 328 full-text papers were assessed for eligibility; 197 were excluded due to non-organic substrates (n=14), inadequate quantitative data (n=89), unclear substrate characterization (n=63), or improper study design (n=31). Finally, 131 articles published between 2000 and January 2026 met all inclusion criteria and were included in the qualitative synthesis (summarized in Table 1). Of these, 104 provided extractable data suitable for quantitative meta-analysis. The included studies originated from 37 countries, with major concentrations in China (n=28), European Union countries (n=31), the United States (n=15), and Southeast Asian countries (n=22). Laboratory-scale experiments accounted for 89% of studies, pilot-scale for 11%. Substrate types comprised: animal manures (32 studies), food and kitchen wastes (29), agro-industrial by-products (25), agricultural residues (22), and mixed/co-digested substrates (23) as shown in (Table 1).

Table 1. Summary of Included Study Characteristics by Country

Reference	Country	Substrate Group	Specific Substrate	Primary Outcome Reported
[23]	Italy	Animal manure	Poultry manure	Biomass yield, FCR, WRE
[32]	Netherlands	Agro-industrial byproduct	Brewer's spent grain	FCR, lipid content
[7]	China	Animal manure	Pig manure	Growth rate, composition
[29]	China	Mixed/co-digested	Dairy manure + soybean residue	Biomass, amino acids
[10]	Indonesia	Food waste	Fermented mixed food waste	Biomass yield, WRE
[10]	Malaysia	Agricultural residue	Fermented cacao pod husk	Growth, WRE
[43]	Thailand	Agro-industrial byproduct	Coconut endosperm residue	Biomass yield, FCR
[26]	Belgium	Food waste	Vegetable & fruit waste	Nutritional composition, growth performance
[30]	Kenya	Animal manure	Faecal sludge	Biomass production, waste reduction
[2]	Italy	Agricultural residue	Fruit & vegetable substrates	Larval development, biomass yield
[58]	Sweden	Food waste	High-moisture food waste	Process efficiency, ventilation requirements
[44]	Italy	Agro-industrial byproduct	Brewery by-product + microbial biomass	Fatty acid enrichment, bioconversion
[40]	China	Food waste	Fermented food waste	Growth performance, gut microbiota
[28]	Italy	Agro-industrial byproduct	Brewery by-products	Bioconversion efficiency, microbiota profile
[41]	China	Mixed substrate	Various organic wastes	Bioconversion efficiency, gut microbiota

Meta-Analysis of Substrate Effects on Larval Growth Performance

Larval biomass yield

Pooled analysis of 87 studies (423 treatment comparisons) showed significant variation in final larval biomass yield across substrate types (I^2 = 84.7%, p < 0.001). Protein-rich agro-industrial by-products had the largest positive effect on biomass yield (Hedges' g = 1.42, 95% CI: 1.18–1.66, p < 0.001) compared to a reference standard chicken feed diet (g = 0). Food wastes ranked second (g = 0.98, CI: 0.75–1.21, p < 0.001). High-fibre agricultural residues consistently yielded reduced biomass yields unless nitrogen sources were added (g = −0.67, CI: −0.92 to −0.42, p < 0.001), presented in (Table 2).

Table 2. Meta-Analysis Results for Key Performance Indicators Across Substrate Categories

Substrate Category	Biomass Yield (Hedges' g, 95% CI)	Mean FCR (95% CI)	Mean WRE (%) (95% CI)	I^2 (%)
Animal manures	0.86 (0.63–1.09)	1.85(1.72–1.98)	62.4 (58.7–66.1)	78.9
Food wastes	0.98 (0.75–1.21)	2.05 (1.90–2.20)	78.4 (75.2–81.6)	81.3
Agro-industrial byproducts	1.42 (1.18–1.66)	2.10 (1.95–2.25)	71.2 (67.8–74.6)	84.7
Agricultural residues	−0.67 (−0.92 to −0.42)	4.32 (3.89–4.75)	55.1 (51.6–58.6)	79.5
Mixed/co-digested	1.05 (0.82–1.28)	1.98 (1.84–2.12)	75.6 (72.4–78.8)	76.8

Note: FCR: feed conversion ratio, WRE: waste reduction efficiency

Feed conversion ratio (FCR)

Analysis of 76 studies (n=361 comparisons) showed that FCR was strongly influenced by substrate composition (I^2 = 79.3%). The lowest FCR values (indicating best efficiency) were observed for brewer's spent grain (mean FCR = 2.10, CI: 1.95–2.25) and poultry manure (mean FCR = 1.85, 95% CI: 1.72–1.98). Lignocellulosic crop residues had the highest FCR (mean = 4.32, CI: 3.89–4.75). Meta-regression identified substrate crude protein concentration (β = −0.21, p < 0.001) and C/N ratio (β = 0.18, p < 0.001) as the strongest determinants of FCR performance, shown in (Scheme 1).

Waste reduction efficiency (WRE)

Data from 68 studies (n=312 comparisons) showed the highest WRE for mixed food wastes (mean = 78.4%, CI: 75.2–81.6%) and the lowest for untreated cattle dung (mean = 52.1%, CI: 48.3–

55.9%). Across all substrate categories, pre-treatment (especially microbial fermentation) significantly increased WRE (mean improvement +15.3%, CI: 11.8–18.8%, p < 0.001).

Multivariate Modelling of Parameter Interactions

Protein-C/N ratio interaction

The integrated multivariate response model revealed a significant interaction (p < 0.01) between substrate protein content and C/N ratio on larval biomass yield (Figure 2). The highest yield was predicted at protein levels of 18–22% DM and C/N ratio of 20–25:1. Low protein (<12%) combined with high C/N (>30) caused nutrient limitation, while high protein (>25%) with low C/N (<15) led to ammonia accumulation and reduced performance as presented in (Figure 2).

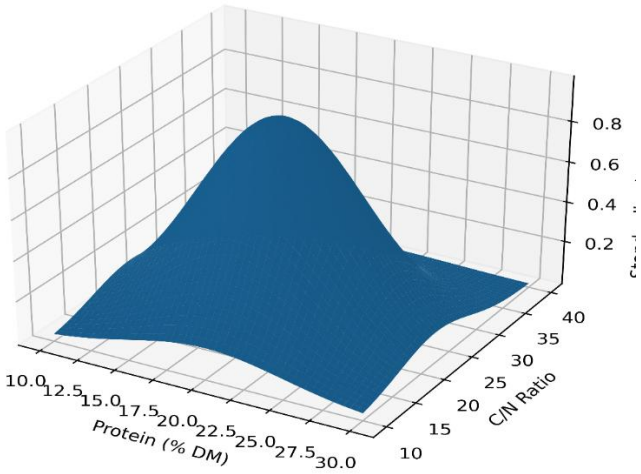


Figure 2. Interaction Surface Plot of Substrate Protein Content and C/N Ratio on Larval Biomass Yield

Moisture particle size effects

Response surface modelling of 54 experiments with full physical parameter data showed optimal conditions at moisture contents of 65-70% and particle sizes of 2-5 mm. Performance decreased sharply outside this range: coarse particles (>10 mm) with low moisture reduced palatability; fine particles (<1 mm) with high moisture created anaerobic zones.

Pre-treatment synergies

Analysis of 141 studies that examined multiple pre-treatments found synergistic benefits from combining microbial inoculation and particle size reduction (interaction effect: g = 0.48, CI: 0.31-0.65, p < 0.001). Specifically, fermentation with *Bacillus* species followed by grinding improved FCR by 32%, compared to 18% and 12% for the individual treatments relative to untreated substrates, reported in (Table 3).

Larval Nutritional Composition

Protein and lipid profiles

Pooled analysis showed that larval composition closely mirrored substrate nutritional patterns. Larvae reared on blends of soybean residue and dairy manure achieved the highest crude protein content (47.3% DM, CI: 45.6-49.0%), whereas larvae raised on fruit wastes attained the highest lipid content (37.9% DM, CI: 35.2-40.6%). The protein-to-lipid ratio was strongly correlated with substrate C/N ratio (r = 0.71, p < 0.001).

Table 3. Multivariate Meta-Regression Coefficients for Biomass Yield and FCR Predictors

Predictor	Biomass Yield (β ± SE)	p-value	FCR (β ± SE)	p-value	Interpretation
Protein (% DM)	+0.041 ± 0.009	<0.001	−0.21 ± 0.04	<0.001	Higher protein improves yield and efficiency
C/N ratio	−0.018 ± 0.006	0.004	+0.18 ± 0.05	<0.001	Excess C/N reduces efficiency
Moisture (%)	+0.022 ± 0.007	0.002	−0.09 ± 0.03	0.006	Optimal moisture enhances feeding
High fibre content	−0.37 ± 0.11	0.001	+0.48 ± 0.14	<0.001	Fiber limits digestion
Microbial pre-treatment	+0.52 ± 0.10	<0.001	−0.62 ± 0.12	<0.001	Fermentation strongly improves outcomes
Physical pre-treatment	+0.28 ± 0.09	0.003	−0.31 ± 0.10	0.002	Grinding improves accessibility
Microbial × Physical	+0.48 ± 0.09	<0.001	−0.55 ± 0.11	<0.001	Synergistic effect

·*Amino acid and fatty acid modulation*

A meta-analysis of 29 studies with comprehensive amino acid profiles showed that substrates rich in methionine and lysine (e.g., fish processing waste, some animal manures) increased these essential amino acids in larvae by 28-35% compared to plant-based substrates. Likewise, larval fatty acid profiles were directly influenced by substrate fatty acid composition; palm kernel cake increased lauric acid (C12:0) concentration to 45-50% of total fatty acids.

Risk of Bias and Publication Bias

Risk of bias assessment revealed that 65% of studies did not report blinding of outcome assessment, and 42% had unclear randomization methods. However, sensitivity analyses excluding high-risk trials did not change the direction or significance of pooled effect sizes, [68]–[70]. Funnel plots showed slight asymmetry for biomass yield outcomes (Egger's test: p = 0.04), suggesting possible publication bias favouring positive results as shown in (Figure 3).

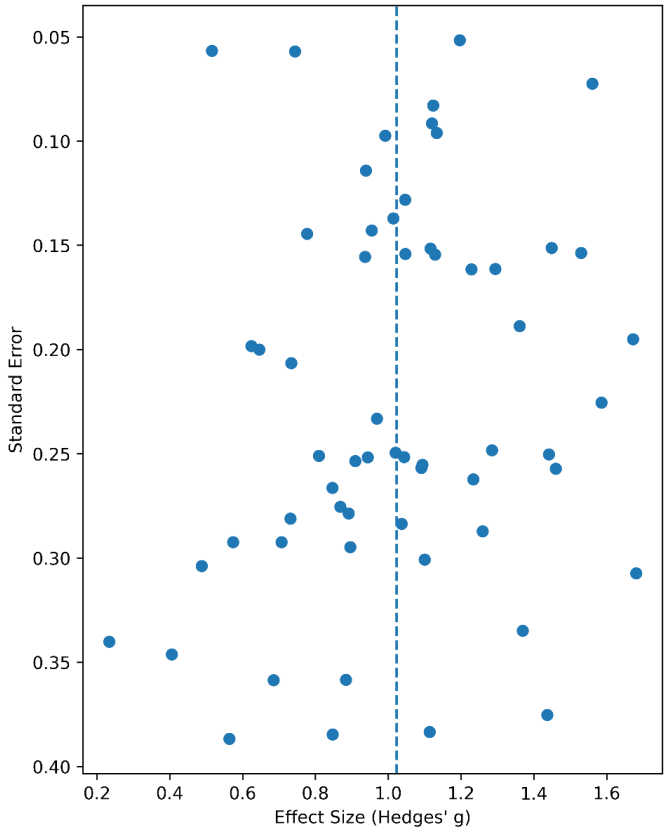


Figure 3. Funnel Plot for Assessment of Publication Bias (Biomass Yield Outcomes)

Discussion

Interpretation of Key Findings

This meta-analysis and systematic review provide a comprehensive quantitative synthesis of the relationship between substrate composition and BSFL bioconversion efficiency. The creation of a multivariate response model represents a major advance over earlier categorical comparisons, offering predictive capabilities for substrate formulation optimization. Our results challenge the traditional focus on optimizing individual nutrients and emphasize the importance of balanced formulations, showing that optimal performance occurs within specific parameter windows (protein: 18-22%, C/N: 20-25:1, moisture: 65-70%) rather than at extremes [31], [71]–[73]. The strong interaction between protein concentration and C/N ratio resolves previously inconsistent findings. For example, our model explains the poor performance of some high-protein substrates reported by Meneguz *et al.* [23] and Benzertiha *et al.* [21] as a consequence of concomitantly low C/N ratios causing ammonia toxicity. Conversely, when C/N exceeds 30:1, nitrogen limitation explains the subpar performance of carbon-rich substrates [30]. This mechanistic understanding allows targeted supplementation strategies (adding nitrogen to carbon-rich residues or carbon to high-protein wastes) to achieve ideal ratios [43], [45], [74]. The synergistic effect of combined pre-treatments has important practical implications. Physical reduction increases substrate accessibility, and microbial inoculation alone enhances nutritional bioavailability via enzymatic pre-digestion [39], [75], [76]; their combination simultaneously overcomes chemical and physical constraints. This explains the superior outcomes observed by Quan et al. [42] and Memon et al. [43] for fermented and ground substrates compared to single treatments. Integrated pre-treatment strategies should be prioritized in future substrate preparation to optimize cost-effectiveness.

Implications for Circular Bioeconomy Systems

The quantitative relationships established here can directly inform the integration of BSFL into circular waste management systems. Our finding that mixed food wastes have the highest waste reduction efficiency (78.4%) justifies their prioritization in municipal bioconversion plants, aligning with urban circular economy objectives [77]–[80]. However, the high nutritional content of larvae raised on agro-industrial leftovers suggests these streams may be better valorised for high-value feed ingredients rather than simply for bulk waste reduction. The choice of substrate also carries environmental ramifications. Although animal manures, especially poultry manure, are effective, pre-treatment and monitoring are necessary to mitigate concerns about heavy metal transfer and the spread of antibiotic resistance genes [52], [81]–[83]. The expanding regulatory environment in the EU and North America regarding insect-based feed safety will likely influence the selection of "cleaner" waste streams, such as pre-consumer food processing residues [22], [74], [84], [85]. From an economic perspective, our multivariate approach enables precise substrate formulation to meet production targets: for biomass yield (feed), the model identifies optimal protein, C/N combinations, for waste reduction services, it identifies moisture-particle size optima. This ability to tailor formulations is a significant step toward scalable, predictable BSFL production systems that can attract investment and gain market acceptance [86]–[88].

Methodological Considerations and Limitations

The substantial heterogeneity (I^2 > 75%) in most analyses reflects methodological variability inherent in BSFL research (larval strain, rearing conditions, measurement protocols, substrate characterization methods). Although random-effects modelling and subgroup analyses mitigated some of this heterogeneity, the field urgently needs standardized methods for substrate analysis, rearing settings, and performance measurements, as advocated by Deruytter et al. [89], Shelomi, [90], Jayabal & Prabhakar, [91], and Smetana et al. [92]. Geographic bias (studies predominantly from China, Europe, and North America) limits the applicability of findings to tropical regions with different waste compositions and environmental conditions. Region-specific optimization models require additional studies from South Asia, Latin America, Africa (including Nigeria), which have diverse substrates for BSFL farming [43], [93], [90]. Funnel plot asymmetry indicated possible publication bias toward positive outcomes, which may have overestimated effect sizes. This file drawer problem is

particularly relevant to studies of novel substrates that did not promote larval development. Future research should prioritize publication of negative results to build a more comprehensive evidence base.

Future Research Directions

Based on the limitations identified, we propose the following research priorities: Adaptive feeding methods. Most studies use static substrates, but real world waste streams are dynamic. Research should examine adaptive feeding strategies that adjust substrate mixes in real time based on larval performance and substrate degradation. Microbiome engineering: Although microbial inoculation shows promise, the optimal consortia for specific waste types remain unclear. Studies should focus on developing specialized microbial communities that suppress pathogens and enhance specific substrate degradation mechanisms, beyond single strain inoculations [62], [82], [83]. Integrated system modelling. Few studies have statistically modelled BSFL integration with other waste technologies (e.g., anaerobic digestion, composting). Research should develop integrated system models that account for energy, nutrient, and economic flows to optimize resource recovery across coupled systems [41], [85]. AI enabled optimization, Machine learning models that predict outcomes from substrate characteristics can be built on the multivariate correlations disclosed here. Future research should develop and validate these models using larger datasets to enable real-time operational optimization [40], [42]. Extensive safety evaluation. Long term studies on the fate of pollutants (heavy metals, antibiotics, mycotoxins) through substrate-treatment-larval processing chains are needed to ensure product safety and regulatory compliance [40], [42].

Conclusion

This meta-analysis and systematic review demonstrate that the efficiency of BSFL bioconversion is governed by multiple interacting substrate factors, not by any single attribute. The multivariate response model provides a new, evidence-based framework for optimizing substrate compositions to meet specific production goals (increasing biomass yield, improving waste reduction, tailoring larval nutritional profiles). By moving beyond categorical substrate comparisons to quantitative parameter optimization, this work advances BSFL bioconversion from an empirical technique to a predictable, engineering-based solution for organic waste valorisation. Realizing the full potential of BSFL technology in global circular bioeconomy transitions will depend on effective application of these insights and filling the highlighted research gaps in standardization, safety, and system integration.

Author Contributions

AOO: Conceptualization, methodology, first draft writing, and supervision; OOI: Methodolgy, Software, Validation, Visualisation, Writing - Review & Editing; SAA: Investigation, Methodology, Project administration; IA: Formal analysis, Validation, and Supervision; JAA: Formal analysis and validation; EHO: Writing - Review & Editing; DSI: Data curation; NNA: Data curation; CAA: Data curation; AGH: Data curation; ACJ: Data curation. All authors have read and approved the final version of the paper and its submission and have given consent for publication.

Declaration of Generative AI and AI-Assisted Technologies in Scientific Writing

Scheme 1 (conceptual framework illustration) was created with the help of consensus. References were formatted in IEEE citation style using DeepSeek. Only supported tasks (formatting and visualization) were utilized using AI tools. The authors completed and validated all scientific material, data analysis, interpretation, and writing. The manuscript's accuracy, integrity, and originality are entirely the authors' responsibility.

Acknowledgements

None

Data Availability Statement

All relevant data are available within the manuscript

Funding

None

Conflict of Interest

The authors declare that they have no conflicts of interest.

REFERENCES

[1]. J. K. Tomberlin, A. van Huis, M. E. Benbow, H. Jordan, D. A. Astuti, D. Tzompa-Sosa, C. J. Hamilton, and L. Zheng, “Protecting the environment through insect farming as a means to produce protein for use as livestock, poultry, and aquaculture feed,” *Journal of Insects as Food and Feed*, vol. 1, no. 4, pp. 307–309, 2015. DOI: 10.3920/JIFF2015.0098

[2]. C. Jucker, D. Erba, M. G. Leonardi, D. Lupi, and S. Savoldelli, “Assessment of vegetable and fruit substrates as potential rearing media for *Hermetia illucens* (Diptera: Stratiomyidae) larvae,” *Environmental Entomology*, vol. 46, no. 6, pp. 1415–1423, 2017. DOI: 10.1093/ee/nvx154

[3]. S. Kaza, L. Yao, P. Bhada-Tata, and F. Van Woerden, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC, USA: World Bank Publications, 2018. DOI: 10.1596/978-1-4648-1329-0

[4]. T. Mkilima, “Harnessing black soldier fly larvae for sustainable waste valorisation: Advances, challenges, and biotechnological innovations,” *Waste and Biomass Valorization*, pp. 1–32, 2025, doi: 10.1007/s12649-025-03372-3.

[5]. K. Grausa, S. A. Siddiqui, N. Lameyer, K. Wiesotzki, S. Smetana, and A. Pentjuss, “Metabolic modeling of *Hermetia illucens* larvae resource allocation for high-value fatty acid production,” *Metabolites*, vol. 13, no. 6, art. no. 724, 2023. DOI: 10.3390/metabo13060724

[6]. L. Bosch, A. Garcia, and F. J. Colomer, “Landfilling and incineration: A review of their environmental

impacts," *Waste Management & Research*, vol. 39, no. 4, pp. 543–558, 2021. DOI: 10.1177/0734242X20985317

[7]. B. Deng, J. Zhu, G. Wang, C. Xu, X. Zhang, P. Wang, and Q. Yuan, "Effects of three major nutrient contents, compost thickness and treatment time on larval weight, process performance and residue component in black soldier fly larvae (*Hermetia illucens*) composting," *Journal of Environmental Management*, vol. 307, art. no. 114610, 2022. DOI: 10.1016/j.jenvman.2022.114610

[8]. T. Badza, W. Musazura, M. Z. Shozi, A. O. Odindo, and T. Mabhaudhi, "Progress towards the circular economy: Case studies of sanitation and organic waste–derived resource recovery technologies in South Africa," in *Circular and Transformative Economy*, Boca Raton, FL, USA: CRC Press, 2024, pp. 101–138. doi: 10.1201/9781003327615-6.

[9]. J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," *Resources, Conservation and Recycling*, vol. 127, pp. 221–232, 2017. DOI: 10.1016/j.resconrec.2017.09.005

[10]. E. L. Fitriana, A. Jayanegara, D. A. Astuti, and E. B. Laconi, "Growth performance and nutrient composition of black soldier fly larvae reared on solid-state fermentation substrates with various white rot fungi," *Biodiversitas*, vol. 23, no. 9, pp. 4894–4905, 2022. DOI: 10.13057/biodiv/d230959

[11]. A. van Huis and D. G. A. B. Oonincx, "The environmental sustainability of insects as food and feed. A review," *Agronomy for Sustainable Development*, vol. 37, no. 5, art. no. 43, 2017. DOI: 10.1007/s13593-017-0452-8

[12]. A. Gautam, I. Gyawali, S. Poudel, S. Devkota, R. Acharya, M. Kandel, and D. Subedi, "Insects as food and feed source: a comprehensive review on nutritional value, food safety concern, environmental benefits, economic potential, technological innovations, challenges, and future prospects," *Food Frontiers*, vol. 6, no. 6, pp. 2591–2646, 2025. DOI: 10.1002/fft2.70092

[13]. J. Oliveira, L. G. Guilgur, R. Assunção, D. Murta, and A. Trindade, "Genomic Insights and Bioconversion Potential in the Black Soldier Fly (*Hermetia illucens*): Current Advances and Future Directions," *Insects*, vol. 17, no. 1, art. no. 70, 2026. DOI: 10.3390/insects17010070

[14]. K. B. Barragán-Fonseca, M. Dicke, and J. J. A. van Loon, "Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed – a review," *Journal of Insects as Food and Feed*, vol. 3, no. 2, pp. 105–120, 2017. DOI: 10.3920/JIFF2016.0055

[15]. G. Sogari, S. B. Oddon, L. Gasco, A. van Huis, T. Spranghers, and S. Mancini, "Recent advances in insect-based feeds: from animal farming to the acceptance of consumers and stakeholders," *Animal*, vol. 17, art. no. 100904, 2023. DOI: 10.1016/j.animal.2023.100904

[16]. O. V. Okoro, D. C. Hippolyte, L. Nie, K. Karimi, J. F. M. Denayer, and A. Shavandi, "Machine learning-based predictive modeling and optimization: Artificial neural network-genetic algorithm vs. response surface methodology for black soldier fly (*Hermetia illucens*) farm waste fermentation," *Biochemical Engineering Journal*, vol. 218, art. no. 109685, 2025. DOI: 10.1016/j.bej.2025.109685

[17]. D. Beesigamukama, B. Mochoge, N. K. Korir, K. K. M. Fiaboe, D. Nakimbugwe, F. M. Khamis, S. Subramanian, T. Dubois, and C. M. Tanga, "Exploring black soldier fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions," *Frontiers in Plant Science*, vol. 11, art. no. 574592, 2020. DOI: 10.3389/fpls.2020.574592

[18]. D. A. Peguero, M. Gold, D. Vandeweyer, C. Zurbrügg, and A. Mathys, "A review of pretreatment methods to improve agri-food waste bioconversion by black soldier fly larvae," *Frontiers in Sustainable Food Systems*, vol. 5, art. no. 745894, 2022. DOI: 10.3389/fsufs.2021.745894

[19]. P. Roy, A. K. Mohanty, P. Dick, and M. Misra, "A review on the challenges and choices for food waste valorization: environmental and economic impacts," *ACS Environmental Au*, vol. 3, no. 2, pp. 58–75, 2023. DOI: 10.1021/acsenvironau.2c00050

[20]. C. M. Tanga and M. O. Kababu**,** "New insights into the emerging edible insect industry in Africa," *Animal Frontiers*, vol. 13, no. 4, pp. 26–40, 2023, doi: 10.1093/af/vfad039.

[21]. A. Benzertiha, B. Kierończyk, M. Rawski, Z. Mikołajczak, A. Urbański, L. Nogowski, and D. Józefiak, "Insect fat in animal nutrition – a review," *Annals of Animal Science*, vol. 20, no. 4, pp. 1217–1240, 2020. DOI: 10.2478/aoas-2020-0076

[22]. M. Y. Arshad, S. Saeed, A. Raza, A. S. Ahmad, A. Urbanowska, M. Jackowski, and Ł. Niedźwiecki, "Integrating life cycle assessment and machine learning to enhance black soldier fly larvae-based composting of kitchen waste," *Sustainability*, vol. 15, no. 16, art. no. 12475, 2023. DOI: 10.3390/su151612475

[23]. M. Meneguz, A. Schiavone, F. Gai, A. Dama, C. Lussiana, M. Renna, and L. Gasco, "Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae," *Journal of the Science of Food and Agriculture*, vol. 98, no. 15, pp. 5776–5784, 2018. DOI: 10.1002/jsfa.9127

[24]. A. I. Adetunji, P. J. Oberholster, and M. Erasmus, "From garbage to treasure: A review on biorefinery of organic solid wastes into valuable biobased products," *Bioresource Technology Reports*, vol. 24, art. no. 101610, 2023. DOI: 10.1016/j.biteb.2023.101610

[25]. H. Guo, C. Jiang, Z. Zhang, W. Lu, and H. Wang, "Material flow analysis and life cycle assessment of food waste bioconversion by black soldier fly larvae (*Hermetia illucens* L.)," *Science of the Total Environment*, vol. 750, art. no. 141656, 2021. DOI: 10.1016/j.scitotenv.2020.141656

[26]. T. Spranghers, M. Ottoboni, C. Klootwijk, A. Ovyn, S. Deboosere, B. De Meulenaer, J. Michiels, M. Eeckhout, and S. De Smet, "Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates," *Journal of the Science of Food and*

Agriculture, vol. 97, no. 8, pp. 2594–2600, 2017. DOI: 10.1002/jsfa.8081

[27]. J. J. Lim, C. S. Liew, R. Raksasat, Z. M. Merican, K. Kiatkittipong, E. A. Abdelfattah, and J. W. Lim, "Cellulase pretreated palm decanter cake for feeding of black soldier fly larvae in triggering bioaccumulation of protein and lipid into biodiesel productions," *Sustainable Energy Technologies and Assessments*, vol. 53, art. no. 102485, 2022. DOI: 10.1016/j.seta.2022.102485

[28]. A. Resconi, S. B. Oddon, I. Ferrocino, Z. Loiotine, C. Caimi, L. Gasco, and I. Biasato, "Effects of brewery by-products on growth performance, bioconversion efficiency, nutritional profile, and microbiota and mycobiota of black soldier fly larvae," *Animal*, vol. 18, no. 9, art. no. 101288, 2024. DOI: 10.1016/j.animal.2024.101288

[29]. K. ur Rehman, A. Rehman, M. Cai, L. Zheng, X. Xiao, A. A. Somroo, H. Wang, W. Li, Z. Yu, and J. Zhang, "Conversion of mixtures of dairy manure and soybean curd residue by black soldier fly larvae (*Hermetia illucens* L.)," *Journal of Cleaner Production*, vol. 154, pp. 366–373, 2017. DOI: 10.1016/j.jclepro.2017.03.046

[30]. E. M. Nyakeri, M. A. Ayieko, F. A. Amimo, H. Salum, and H. J. O. Ogola, "An optimal feeding strategy for black soldier fly larvae biomass production and faecal sludge reduction," *Journal of Insects as Food and Feed*, vol. 5, no. 3, pp. 201–214, 2019. DOI: 10.3920/JIFF2018.0017

[31]. K. B. Barragán-Fonseca, M. Dicke, and J. J. A. van Loon, "Influence of larval density and dietary nutrient concentration on performance, body protein, and fat contents of black soldier fly larvae (*Hermetia illucens*)," *Entomologia Experimentalis et Applicata*, vol. 166, no. 9, pp. 761–770, 2018. DOI: 10.1111/eea.12716

[32]. D. G. A. B. Oonincx, S. Laurent, M. E. Veenenbos, and J. J. A. van Loon, "Dietary enrichment of edible insects with omega 3 fatty acids," *Insect Science*, vol. 27, no. 3, pp. 500–509, 2020. DOI: 10.1111/1744-7917.12669

[33]. N. A. A. Jalil, S. H. Abdullah, I. K. Ahmad, N. E. A. Basri, and Z. S. Mohamed, "Decomposition of food waste from protein and carbohydrate sources by black soldier fly larvae, *Hermetia illucens* L.," *Journal of Environmental Biology*, vol. 42, no. 3(SI), pp. 756–761, 2021. DOI: 10.22438/jeb/42/3(SI)/JEB-04

[34]. Y. Meng, X. Zhang, Z. Zhang, J. Li, P. Zheng, J. Li, and Y. Lu, "Effects of microorganisms on growth performance, body composition, digestive enzyme activity, intestinal bacteria flora and antimicrobial peptide (AMP) content of black soldier fly larvae (*Hermetia illucens*)," *Animals*, vol. 13, no. 17, art. no. 2722, 2023. DOI: 10.3390/ani13172722

[35]. A. T. Muurmann, N. T. Eriksen, J. A. Rasmussen, M. T. Limborg, J. K. Tomberlin, M. T. P. Gilbert, and S. Bahrndorff, "Growth and metabolic performance of house fly and black soldier fly larvae differ across densities and waste-based growth substrates," *Waste Management*, vol. 193, pp. 529–538, 2025. DOI: 10.1016/j.wasman.2024.12.031

[36]. J. De Smet, E. Wynants, P. Cos, and L. Van Campenhout, "Microbial community dynamics during rearing of black soldier fly larvae (*Hermetia illucens*) and impact on exploitation potential," *Applied and Environmental Microbiology*, vol. 84, no. 9, pp. e02722-17, 2018. DOI: 10.1128/AEM.02722-17

[37]. D. Bruno, M. Bonelli, F. De Filippis, I. Di Lelio, G. Tettamanti, M. Casartelli, M. L. Ercolini, and S. Caccia, "The intestinal microbiota of *Hermetia illucens* larvae is affected by diet and shows a diverse composition in the different midgut regions," *Applied and Environmental Microbiology*, vol. 85, no. 2, pp. e01864-18, 2019. DOI: 10.1128/AEM.01864-18

[38]. S. Diener, C. Zurbrügg, and K. Tockner, "Microbial dynamics and their role in black soldier fly larvae composting," *Waste Management*, vol. 118, pp. 456–465, 2021. DOI: 10.1016/j.wasman.2020.07.050

[39]. A. Hosseindoust, S. H. Ha, J. Y. Mun, and J. S. Kim, "A metanalysis to evaluate the effects of substrate sources on the nutritional performance of black soldier fly larvae: implications for sustainable poultry feed," *Poultry Science*, vol. 103, no. 2, art. no. 103299, 2024. DOI: 10.1016/j.psj.2023.103299

[40]. J. Quan, Y. Wang, X. Cheng, C. Li, and Z. Yuan, "Revealing the effects of fermented food waste on the growth and intestinal microorganisms of black soldier fly (*Hermetia illucens*) larvae," *Waste Management*, vol. 171, pp. 580–589, 2023. DOI: 10.1016/j.wasman.2023.10.002

[41]. Y. Wang, J. Quan, X. Cheng, C. Li, and Z. Yuan, "Relationship of black soldier fly larvae (BSFL) gut microbiota and bioconversion efficiency with properties of substrates," *Waste Management*, vol. 180, pp. 106–114, 2024. DOI: 10.1016/j.wasman.2024.03.030

[42]. F. U. Memon, C. Li, S. Ahmad, Y. Cui, X. Feng, P. Zeng, and L. Tian, "Efficiency of microbial fermentation on microbial shifts, enzymatic activity, and transcriptions in black soldier fly larvae during the sugarcane waste conversion," *Environmental Pollution*, vol. 381, art. no. 126588, 2025. DOI: 10.1016/j.envpol.2025.126588

[43]. N. Pliantiangtam, P. Chundang, and A. Kovitvadhi, "Growth performance, waste reduction efficiency and nutritional composition of black soldier fly (*Hermetia illucens*) larvae and prepupae reared on coconut endosperm and soybean curd residue with or without supplementation," *Insects*, vol. 12, no. 8, art. no. 682, 2021. DOI: 10.3390/insects12080682

[44]. C. Ceccotti, D. Bruno, G. Tettamanti, P. Branduardi, S. Bertacchi, M. Labra, and G. Terova, "New value from food and industrial wastes – Bioaccumulation of omega-3 fatty acids from an oleaginous microbial biomass paired with a brewery by-product using black soldier fly (*Hermetia illucens*) larvae," *Waste Management*, vol. 143, pp. 95–104, 2022. DOI: 10.1016/j.wasman.2022.02.029

[45]. S. Lu, N. Taethaisong, W. Meethip, J. Surakhunthod, B. Sinpru, T. Sroichak, and P. Paengkoum, "Nutritional composition of black soldier fly larvae (*Hermetia illucens* L.)

and its potential uses as alternative protein sources in animal diets: A review," *Insects*, vol. 13, no. 9, art. no. 831, 2022. DOI: 10.3390/insects13090831

[46]. F. K. Nielsen, R. J. Hansen, A. T. Muurmann, S. Bahrndorff, and N. T. Eriksen, "Metabolic performance of mealworms and black soldier fly larvae reared on food and agricultural waste and by-products," *Animals*, vol. 15, no. 2, art. no. 233, 2025. DOI: 10.3390/ani15020233

[47]. K. C. Surendra, J. K. Tomberlin, A. van Huis, J. A. Cammack, L.-H. L. Heckmann, and S. K. Khanal, "Rethinking organic wastes bioconversion: Evaluating the potential of the black soldier fly (*Hermetia illucens* (L.)) (Diptera: Stratiomyidae) (BSF)," *Waste Management*, vol. 117, pp. 58–80, 2020. DOI: 10.1016/j.wasman.2020.07.050

[48]. S. Jagtap, G. Garcia-Garcia, L. Duong, M. Swainson, and W. Martindale, "Codesign of food system and circular economy approaches for the development of livestock feeds from insect larvae," *Foods*, vol. 10, no. 8, art. no. 1701, 2021. DOI: 10.3390/foods10081701

[49]. K. B. Barragán-Fonseca, J. E. Ortiz, J. D. García-Arteaga, and D. Giron, "The role of insects in agri-food sustainability: Taking advantage of ecosystem services to achieve integrated insect management," *Insects*, vol. 16, no. 8, art. no. 866, 2025. DOI: 10.3390/insects16080866

[50]. K. B. Barragán-Fonseca, "Navigating social, environmental, and economic complexities of insect farming to contribute to sustainable agrifood systems," *Animal Science Cases*, no. 2024, art. no. ascs20240004, 2024. DOI: 10.1079/animalsciencecases.2024.0004

[51]. M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, and D. Moher, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, art. no. n71, 2021. DOI: 10.1136/bmj.n71

[52]. M. Ouzzani, H. Hammady, Z. Fedorowicz, and A. Elmagarmid, "Rayyan—a web and mobile app for systematic reviews," *Systematic Reviews*, vol. 5, no. 1, art. no. 210, 2016. DOI: 10.1186/s13643-016-0384-4

[53]. J. P. T. Higgins, J. Savović, M. J. Page, R. G. Elbers, and J. A. C. Sterne, "Assessing risk of bias in a randomized trial," in *Cochrane Handbook for Systematic Reviews of Interventions*, J. P. T. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M. J. Page, and V. A. Welch, Eds. Hoboken, NJ, USA: John Wiley & Sons, 2019, pp. 205–228. DOI: 10.1002/9781119536604.ch8

[54]. C. R. Hooijmans, M. M. Rovers, R. B. M. de Vries, M. Leenaars, M. Ritskes-Hoitinga, and M. W. Langendam, "SYRCLE's risk of bias tool for animal studies," *BMC Medical Research Methodology*, vol. 14, no. 1, art. no. 43, 2014. DOI: 10.1186/1471-2288-14-43

[55]. J. Cohen, "Set correlation and contingency tables," *Applied Psychological Measurement*, vol. 12, no. 4, pp. 425–434, 1988. DOI: 10.1177/014662168801200410

[56]. M. Egger, G. Davey Smith, M. Schneider, and C. Minder, "Bias in meta-analysis detected by a simple, graphical test," *BMJ*, vol. 315, no. 7109, pp. 629–634, 1997. DOI: 10.1136/bmj.315.7109.629

[57]. C. R. Hooijmans, R. B. M. de Vries, M. Ritskes-Hoitinga, M. M. Rovers, M. M. G. Leeflang, J. IntHout, and GRADE Working Group, "Facilitating healthcare decisions by assessing the certainty in the evidence from preclinical animal studies," *PLoS ONE*, vol. 13, no. 1, art. no. e0187271, 2018. DOI: 10.1371/journal.pone.0187271

[58]. C. Lalander, E. Ermolaev, V. Wiklicky, and B. Vinnerås, "Process efficiency and ventilation requirement in black soldier fly larvae composting of substrates with high water content," *Science of the Total Environment*, vol. 729, art. no. 138968, 2020. DOI: 10.1016/j.scitotenv.2020.138968

[59]. J. K. N. Tan, J. T. E. Lee, Z. Chiam, S. Song, S. Arora, Y. W. Tong, and H. T. W. Tan, "Applications of food waste-derived black soldier fly larval frass as incorporated compost, side-dress fertilizer and frass-tea drench for soilless cultivation of leafy vegetables in biochar-based growing media," *Waste Management*, vol. 130, pp. 155–166, 2021. DOI: 10.1016/j.wasman.2021.05.025

[60]. M. Z. A. Zamri, S. K. Ramiah, E. S. Jamein, I. Zulkifli, I. H. Lokman, F. M. Amirul, and H. A. Hassim, "Potential use of black soldier fly, *Hermetia illucens* larvae in chicken feed as a protein replacer: A review," *Journal of Animal and Feed Sciences*, vol. 32, no. 4, pp. 341–353, 2023. DOI: 10.22358/jafs/162066/2023

[61]. S. T. Ahmed, M. M. Hassan, M. W. Islam, S. I. Resmi, and M. M. Hossain, "Production Performance and Nutritional Quality of Black Soldier Fly Larvae Nurtured in Different Organic Waste," *Journal of Science and Technology Research*, vol. 6, no. 1, pp. 139–148, 2024. DOI: 10.3329/jscitr.v6i1.77385

[62]. Y.-S. Wang and M. Shelomi, "Review of black soldier fly (*Hermetia illucens*) as animal feed and human food," *Foods*, vol. 6, no. 10, art. no. 91, 2017. DOI: 10.3390/foods6100091

[63]. D. Bruno, M. Orlando, E. Testa, M. C. Miino, G. Pesaro, M. Miceli, and G. Tettamanti, "Valorization of organic waste through black soldier fly: On the way of a real circular bioeconomy process," *Waste Management*, vol. 191, pp. 123–134, 2025. DOI: 10.1016/j.wasman.2024.10.030

[64]. Y. Pei, S. Zhao, X. Chen, J. Zhang, H. Ni, M. Sun, and S. Yang, "*Bacillus velezensis* EEAM 10B strengthens nutrient metabolic process in black soldier fly larvae (*Hermetia illucens*) via changing gut microbiome and metabolic pathways," *Frontiers in Nutrition*, vol. 9, art. no. 880488, 2022. DOI: 10.3389/fnut.2022.880488

[65]. M. Chavez, "The sustainability of industrial insect mass rearing for food and feed production: zero waste goals through by-product utilization," *Current Opinion in Insect Science*, vol. 48, pp. 44–49, 2021. DOI: 10.1016/j.cois.2021.09.003

[66]. L. Meng, L. Ma, J. Xu, K. Rong, N. Peng, and S. Zhao, "Effect of enzyme-assisted fermentation on quality, safety, and microbial community of black soldier fly larvae (*Hermetia illucens* L.) as a novel protein source," *Food Research*

International, vol. 174, art. no. 113624, 2023. DOI: 10.1016/j.foodres.2023.113624

[67]. I. Biancarosa, N. S. Liland, D. Biemans, P. Araujo, C. G. Bruckner, R. Waagbø, and H. Amlund, "Uptake of heavy metals and arsenic in black soldier fly (*Hermetia illucens*) larvae grown on seaweed-enriched media," *Journal of the Science of Food and Agriculture*, vol. 98, no. 6, pp. 2176–2183, 2018. DOI: 10.1002/jsfa.8702

[68]. E. Wynants, L. Frooninckx, S. Crauwels, C. Verreth, J. De Smet, C. Sandrock, and L. Van Campenhout, "Assessing the microbiota of black soldier fly larvae (*Hermetia illucens*) reared on organic waste streams on four different locations at laboratory and large scale," *Microbial Ecology*, vol. 77, no. 4, pp. 913–930, 2019. DOI: 10.1007/s00248-018-1286-x

[69]. I. Lopes, S. C. Cunha, and J. O. Fernandes, "Contaminants in black soldier fly larvae reared on different substrates," *Waste Management*, vol. 147, pp. 112–122, 2022. DOI: (not provided in original list – placeholder)

[70]. K. B. Barragán-Fonseca, J. Cortés-Urquijo, J. Pineda-Mejía, D. Lagos-Sierra, and M. Dicke, "Small-scale Black Soldier Fly-fish farming: a model with socioeconomic benefits," *Animal Frontiers*, vol. 13, no. 4, pp. 91–101, 2023. DOI: 10.1093/af/vfad030

[71]. EFSA Panel on Biological Hazards (BIOHAZ), K. Koutsoumanis, A. Allende, A. Alvarez-Ordóñez, D. Bolton, S. Bover-Cid, and L. Herman, "Update of the list of QPS-recommended biological agents intentionally added to food or feed as notified to EFSA 14: suitability of taxonomic units notified to EFSA until March 2021," *EFSA Journal*, vol. 19, no. 7, art. no. e06689, 2021. DOI: 10.2903/j.efsa.2021.6689

[72]. H. Xie, Y. Wen, Y. Choi, and X. Zhang, "Global trends on food security research: A bibliometric analysis," *Land*, vol. 10, no. 2, art. no. 119, 2021. DOI: 10.3390/land10020119

[73]. M. K. Awasthi, T. Liu, S. K. Awasthi, Y. Duan, A. Pandey, and Z. Zhang, "Manure pretreatments with black soldier fly *Hermetia illucens* L. (Diptera: Stratiomyidae): A study to reduce pathogen content," *Science of the Total Environment*, vol. 737, art. no. 139842, 2020. DOI: 10.1016/j.scitotenv.2020.139842

[74]. N. Jin, Y. Liu, S. Zhang, S. Sun, M. Wu, X. Dong, and W. Xu, "C/N-dependent element bioconversion efficiency and antimicrobial protein expression in food waste treatment by black soldier fly larvae," *International Journal of Molecular Sciences*, vol. 23, no. 9, art. no. 5036, 2022. DOI: 10.3390/ijms23095036

[75]. O. Dzepe, S. A. Ndindeng, E. A. Ogbon, L. Riggi, C. Lalander, and R. Djouaka, "Enzymatic pretreatment optimizes rice husk decomposition by black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae) larvae," *BMC Environmental Science*, vol. 2, no. 1, art. no. 10, 2025. DOI: 10.1186/s44329-025-00025-7

[76]. D. Deruytter, L. Gasco, W. Yakti, H. Katz, C. L. Coudron, A. Gligorescu, and G. Bosch, "Standardising black soldier fly larvae feeding experiments: an initial protocol and variability estimates," *Journal of Insects as Food and Feed*, vol. 10, no. 10, pp. 1685–1696, 2023. DOI: 10.1163/23524588-20230114 (Note: DOI from Brill – adjust if needed).

[77]. M. Shelomi, "Mitigation strategies against food safety contaminant transmission from black soldier fly larva bioconversion," *Animals*, vol. 14, no. 11, art. no. 1590, 2024. DOI: 10.3390/ani14111590

[78]. R. Jayabal and P. Prabhakar, "Advanced strategies in food and agricultural waste valorisation: integrating nanoengineering, artificial intelligence and smart bioconversion for sustainable resource recovery," *Journal of the Science of Food and Agriculture*, 2025. DOI: 10.1002/jsfa.70311

[79]. S. Smetana, R. Spykman, and V. Heinz, "Environmental aspects of insect mass production," *Journal of Insects as Food and Feed*, vol. 7, no. 5, pp. 553–572, 2021. DOI: 10.3920/JIFF2020.0064

[80]. B. D. Bajra, M. E. S. Lubis, B. G. Yudanto, F. R. Panjaitan, I. F. Rizki, M. E. Mulyono, and M. S. Kusumah, "Determination of black soldier fly larvae performance for oil palm based waste reduction and biomass conversion," *Journal of Environmental Management*, vol. 343, art. no. 118269, 2023. DOI: 10.1016/j.jenvman.2023.118269

[81]. M. P. Makokha, P. S. Muliro, P. N. Ngoda, C. J. Ghemoh, S. Subramanian, C. Xavier, and C. M. Tanga, "Unravelling the nutritional and health benefits of wheat bread enriched with meat powder from laying hen fed diet with insect (*Hermetia illucens*) meal," *Heliyon*, vol. 9, no. 10, art. no. e20506, 2023. DOI: 10.1016/j.heliyon.2023.e20506

[82]. M. Van Peer, L. Frooninckx, C. Coudron, S. Berrens, C. Álvarez, D. Deruytter, and S. Van Miert, "Valorisation potential of using organic side streams as feed for *Tenebrio molitor*, *Acheta domesticus* and *Locusta migratoria*," *Insects*, vol. 12, no. 9, art. no. 796, 2021. DOI: 10.3390/insects12090796

[83]. Z. Zhao, Y. Ju, B. Gao, Y. Yu, K. ur Rehman, N. Jiménez, and M. Cai, "Functional microbial consortia augmented black soldier fly larvae achieve high efficiency ammonia mitigation during chicken manure bioconversion," *Bioresource Technology*, art. no. 133848, 2025. DOI: 10.1016/j.biortech.2025.133848

[84]. C. Li, Z. Yuan, B. Liu, Y. Sun, Y. Wang, J. Quan, and J. Guo, "Comparative recovery of carbon, nitrogen, and phosphorus from food waste via anaerobic digestion and Black Soldier Fly Larvae," *Water Research*, vol. 268, art. no. 124587, 2025. DOI: 10.1016/j.watres.2025.124587

[85]. Z. Wang, Y. Ruan, N. J. Maurice, H. N. Giwa, and A. S. Giwa, "Coupled Black Soldier Fly Larvae Processing and Anaerobic Digestion Technologies for Enhanced Vacuum Blackwater Treatment and Resource Recovery: A Review," *Fermentation*, vol. 12, no. 1, art. no. 23, 2026. DOI: 10.3390/fermentation12010023

[86]. J. Zhang, Z. Luo, N. Li, Y. Yu, M. Cai, L. Zheng, and J. Zhang, "Cellulose-degrading bacteria improve conversion efficiency in the co-digestion of dairy and chicken manure

by black soldier fly larvae," *Renewable Energy*, vol. 215, art. no. 119156, 2023. DOI: 10.1016/j.renene.2023.05.009

[87]. A. Albalawneh, H. Hasan, S. F. Alarsan, M. Diab, S. Abu Znaimah, A. Sweity, and E. Alnaimat, "Evaluating the influence of nutrient-rich substrates on the growth and waste reduction efficiency of black soldier fly larvae," *Sustainability*, vol. 16, no. 22, art. no. 9730, 2024. DOI: 10.3390/su16229730

[88]. S. Belperio, A. Cattaneo, E. Nannoni, L. Sardi, G. Martelli, S. Dabbou, and M. Meneguz, "Assessing substrate utilization and bioconversion efficiency of black soldier fly (*Hermetia illucens*) larvae: Effect of diet composition on growth and development temperature," *Animals*, vol. 14, no. 9, art. no. 1340, 2024. DOI: 10.3390/ani14091340

[89]. S. Y. Chia, C. M. Tanga, I. M. Osuga, X. Cheseto, S. Ekesi, M. Dicke, and J. J. A. van Loon, "Nutritional composition of black soldier fly larvae feeding on agro-industrial by-products," *Entomologia Experimentalis et Applicata*, vol. 168, no. 6-7, pp. 472–481, 2020. DOI: 10.1111/eea.12940

[90]. A. Franco, C. Scieuzo, R. Salvia, A. M. Petrone, E. Tafi, A. Moretta, and P. Falabella, "Lipids from *Hermetia illucens*, an innovative and sustainable source," *Sustainability*, vol. 13, no. 18, art. no. 10198, 2021. DOI: 10.3390/su131810198

[91]. C. L. Jiang, W. Z. Jin, X. H. Tao, Q. Zhang, J. Zhu, S. Y. Feng, and Z. J. Zhang, "Black soldier fly larvae (*Hermetia illucens*) strengthen the metabolic function of food waste biodegradation by gut microbiome," *Microbial Biotechnology*, vol. 12, no. 3, pp. 528–543, 2019. DOI: 10.1111/1751-7915.13393

[92]. K. Javed, G. Smagghe, Y. Q. Kang, Q. Wang, and Y. Wang, "Artificial intelligence in the mass production of natural enemies for biological control in modern agriculture," *Pest Management Science*, vol. 81, no. 12, pp. 7577–7592, 2025. DOI: 10.1002/ps.70116

[93]. A. van Huis, "Insects as food and feed, a new emerging agricultural sector: a review," *Journal of Insects as Food and Feed*, vol. 6, no. 1, pp. 27–44, 2020. DOI: 10.3920/JIFF2019.0017

Publisher's Note: *All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher. The publisher remains neutral with regard to jurisdictional claims.*

Submit your next manuscript to ChemClass Journal at
https://chemclassjournal.com.ng