



# Global black soldier fly bioconversion for organic waste and climate change mitigation: A systematic review

Stephen Bishibura Erick<sup>1</sup>  
Twalibu Bella<sup>2</sup>  
Bonamax Mbasa<sup>3</sup>

<sup>1</sup>[serick@irdp.ac.tz](mailto:serick@irdp.ac.tz)

<sup>2</sup>[tbell@irdp.ac.tz](mailto:tbell@irdp.ac.tz)

<sup>3</sup>[bmbasa@irdp.ac.tz](mailto:bmbasa@irdp.ac.tz)

<sup>1</sup><https://orcid.org/0009-0007-1400-9734>

<sup>2</sup><https://orcid.org/0009-0008-6205-3622>

<sup>3</sup><https://orcid.org/0009-0007-8072-6408>

<sup>1,2,3</sup>Institute of Rural Development Planning, Tanzania

<https://doi.org/10.51867/scimundi.6.1.16>

---

## ABSTRACT

Organic waste management represents a systemic sustainability challenge within linear production–consumption regimes. Black soldier fly (*Hermetia illucens*) bioconversion has emerged as a bio-based pathway capable of simultaneously reducing waste volumes and generating value-added outputs. This systematic review synthesizes 156 studies (2010–2025) using PRISMA-guided methods and integrates meta-analysis with thematic analysis. Results indicate significantly lower greenhouse gas emissions compared to landfilling, composting, and incineration (Hedges'  $g = -2.84$ ; 95% CI:  $-3.21$  to  $-2.47$ ), despite high heterogeneity ( $I^2 = 78.4\%$ ). Mean waste reduction reached 82.3%, with strong scale effects in economic performance. Regulatory fragmentation remains a structural constraint. Situated within circular economy and industrial ecology frameworks, these findings suggest that BSF systems function as context-dependent mechanisms for material recirculation and bio-based substitution. Their contribution to circular bioeconomy transitions depends on regulatory harmonization, methodological standardization, and locally embedded implementation strategies.

**Keywords:** Black Soldier Fly, Circular Bioeconomy, Life Cycle Assessment, Organic Waste Bioconversion, Systematic Review

---

## I. INTRODUCTION

Organic waste management has become a significant environmental and governance challenge of the twenty first century. Rapid urbanization, demographic growth, and changing consumption patterns have increased the volume of municipal solid waste generated globally, with biodegradable organic materials constituting a substantial proportion of total waste streams (Kaza et al., 2018). When inadequately managed, organic waste contributes to methane emissions from landfills and nitrous oxide release during decomposition, thereby contributing to climate change (IPCC, 2021). Conventional treatment pathways, including landfilling, composting, and incineration, involve trade offs related to greenhouse gas emissions, land use requirements, and limited resource recovery (Wilson et al., 2015; UNEP, 2021). These constraints have prompted examination of alternative strategies capable of reducing environmental impacts while recovering material value.

Biological valorization approaches have gained attention as mechanisms that convert organic residues into usable outputs. Among these, black soldier fly (*Hermetia illucens*) bioconversion has been examined as a resource recovery technology (van Huis, 2020; Klammsteiner et al., 2022). Black soldier fly larvae are able to process a range of organic substrates, including food waste, agricultural residues, and certain manure streams, into protein rich biomass and nutrient containing frass suitable for soil application (Bonelli et al., 2019; Parodi et al., 2021). This functional combination links waste management with feed production and nutrient cycling.

Interest in BSF systems is associated with broader discussions surrounding circular economy and circular bioeconomy frameworks. Circular economy theory challenges linear production models and emphasizes regenerative systems in which materials retain value through repeated cycles of use and recovery (Papargyropoulou et al., 2014). Within this perspective, organic residues are viewed as secondary resources rather than terminal waste streams. Industrial ecology extends this systems orientation through analysis of material and energy flows across interconnected production systems. Life cycle assessment provides a method for evaluating environmental performance across input, processing, and substitution stages (Mertenat et al., 2019; Parodi et al., 2021).



Empirical findings concerning BSF bioconversion show variability across operational contexts. Life cycle assessments report differing greenhouse gas outcomes depending on system boundaries, allocation approaches, substrate composition, and energy sources (Mertenat et al., 2019; Parodi et al., 2021; Ronda et al., 2023). In certain configurations, BSF treatment is associated with lower emissions relative to conventional waste management pathways. In other contexts, environmental gains are moderated through energy requirements for climate control and transportation (Grossule & Lavagnolo, 2023; Rochimawati et al., 2025).

Economic performance also varies across scales and locations. Outcomes depend on facility size, labor costs, energy prices, regulatory compliance requirements, and feed market conditions (Batool et al., 2024; Ghandy, Koen & Gumilang, 2025). Larger facilities often report higher internal rates of return, whereas smaller operations encounter higher unit costs and longer payback periods. In contrast to conventional waste treatment systems that depend primarily on tipping fees (Hoornweg and Bhada Tata, 2012), BSF enterprises frequently rely on revenue from protein meal, oil products, and soil amendments (Bruno et al. 2025; Reyes Torres et al., 2022).

Regulatory conditions further influence adoption patterns. Approval processes for insect derived feed differ across jurisdictions, particularly in relation to substrate eligibility and authorized livestock categories (Dobersek et al., 2023; Vantomme and Geuens, 2023). Variation in regulatory frameworks affects compliance costs, trade opportunities, and scalability (Everitt et al., 2023). These factors indicate that environmental performance alone does not determine implementation outcomes; rather, environmental, economic, and institutional dimensions interact in shaping diffusion trajectories.

Previous reviews have addressed individual aspects of BSF systems, including waste reduction efficiency, nutritional characteristics, and environmental assessment (Gonçalves Matos, 2023; Malmström et al., 2016). However, fewer studies have examined environmental, economic, and regulatory dimensions within a single analytical framework. Continued expansion of empirical research warrants updated synthesis incorporating recent life cycle analyses and commercial scale evidence. Clarification is needed regarding the conditions under which BSF bioconversion contributes to circular bioeconomy objectives. This study provides an integrated assessment of environmental performance, economic feasibility, and regulatory alignment within circular economy and industrial ecology perspectives. The analysis evaluates whether BSF systems operate as context dependent mechanisms for material recirculation, nutrient recovery, and greenhouse gas mitigation across different operational and institutional settings.

Specifically, this review pursues four objectives. First, it quantifies the environmental performance of black soldier fly bioconversion relative to conventional organic waste treatment pathways. Second, it assesses economic feasibility across operational scales and geographic contexts. Third, it examines regulatory and institutional frameworks governing BSF implementation. Fourth, it identifies barriers, enabling factors, and research gaps influencing large scale adoption and sustainability outcomes.

The remainder of the paper is organized as follows. Section II outlines the theoretical foundations grounded in circular economy and industrial ecology scholarship. Section III describes the systematic review protocol, search strategy, eligibility criteria, and analytical procedures. Section IV presents empirical findings and integrates quantitative and qualitative results. Section V discusses implications for sustainability transitions and circular bioeconomy policy. Section VI concludes with recommendations for research, regulation, and implementation.

## 1.2 Research Objective (s)

This study examines the role of black soldier fly (*Hermetia illucens*) bioconversion within circular bioeconomy transitions through an integrated assessment of environmental, economic, and regulatory dimensions. The review is guided by the following objectives:

1. To quantify the environmental performance of black soldier fly bioconversion relative to conventional organic waste treatment pathways, with particular attention to greenhouse gas emissions, waste reduction efficiency, and resource use.
2. To evaluate economic feasibility across operational scales and geographic contexts, including capital investment requirements, operating costs, and financial performance indicators.
3. To analyze regulatory and institutional frameworks governing black soldier fly implementation, focusing on approval processes, substrate restrictions, and market authorization conditions.
4. To identify key barriers, enabling factors, and research gaps that influence the adoption and sustainability outcomes of black soldier fly systems.



## II. THEORETICAL REVIEW

We ground our analysis in two complementary theoretical traditions: circular economy theory and industrial ecology. Circular economy thinking rejects the linear “take-make-dispose” model and insists that materials should retain their value through regenerative loops (Papargyropoulou et al., 2014). Organic residues, from this viewpoint, are not waste but recoverable resources whose transformation can generate benefits well beyond the waste management sector. But circularity at the process level does not guarantee sustainability at the system level. Whether resource loops actually close depends on environmental efficiency, what products get displaced, and whether institutions can support the transition.

Industrial ecology adds to this by tracing material and energy flows across interconnected production systems. Life cycle assessment serves as a principal analytical tool for evaluating environmental impacts across production, processing, and substitution stages (Parodi et al., 2021; Mertenat et al., 2019). For insect-based waste conversion specifically, greenhouse gas outcomes hinge on choices about allocation methods, energy sources, and scale of operation (Ronda et al., 2023). Point estimates of performance without system-level context can be misleading.

A third dimension matters just as much: the regulatory and institutional landscape. Approval pathways for insect-derived feed, restrictions on which substrates can be used, and biosecurity standards all vary widely between jurisdictions (Dobersek et al., 2023; Vantomme & Geuens, 2023). Drawing on sustainability transitions thinking, we recognize that environmental performance alone does not drive adoption. Economic incentives and governance frameworks must also align for a technology to move from niche experimentation toward mainstream use. These three lenses (environmental performance, economic viability, and institutional alignment) structure our review. They give us a framework for making sense of a body of evidence that is large, growing, and highly variable.

## III. METHODOLOGY

### 3.1 Protocol and Registration

We followed the PRISMA 2020 guidelines (Page et al., 2021). A structured protocol was developed before we began screening to keep eligibility decisions and data extraction consistent. PROSPERO registration is standard in clinical systematic reviews (Booth et al., 2012) but its scope is limited to health and medical intervention studies. Because our review spans environmental science, economics, and regulatory analysis, PROSPERO registration was not appropriate. We followed established systematic review standards throughout to maintain transparency.

### 3.2 Literature Search Strategy

We searched five databases between September 2024 and January 2025: Web of Science Core Collection, Scopus, PubMed MEDLINE, ScienceDirect, and Google Scholar. Web of Science and Scopus gave us broad multidisciplinary coverage. PubMed MEDLINE captured the entomological and biological literature on *Hermetia illucens*. ScienceDirect added further coverage of environmental and applied science journals.

We used Google Scholar as a supplementary source for grey literature, including theses and technical reports. Its search algorithms are not fully transparent or reproducible, a known limitation (Gusenbauer & Haddaway, 2020). Search strings combined organism specific terms with waste management and environmental impact terminology. The primary search string integrated references to black soldier fly, organic waste treatment, greenhouse gas emissions, climate change, and life cycle assessment. Additional searches captured literature addressing circular economy dimensions, protein production, animal feed applications, and commercial scale operations. Search terms were adapted across databases to accommodate indexing structures while maintaining conceptual equivalence.

### 3.3 Eligibility Criteria

We set eligibility criteria before screening began (Higgins et al., 2023). We included studies from January 2010 to January 2025. The 2010 start date marks the period when commercial BSF applications and related regulation began to expand meaningfully. Only English-language publications were included, as we lacked systematic translation resources.

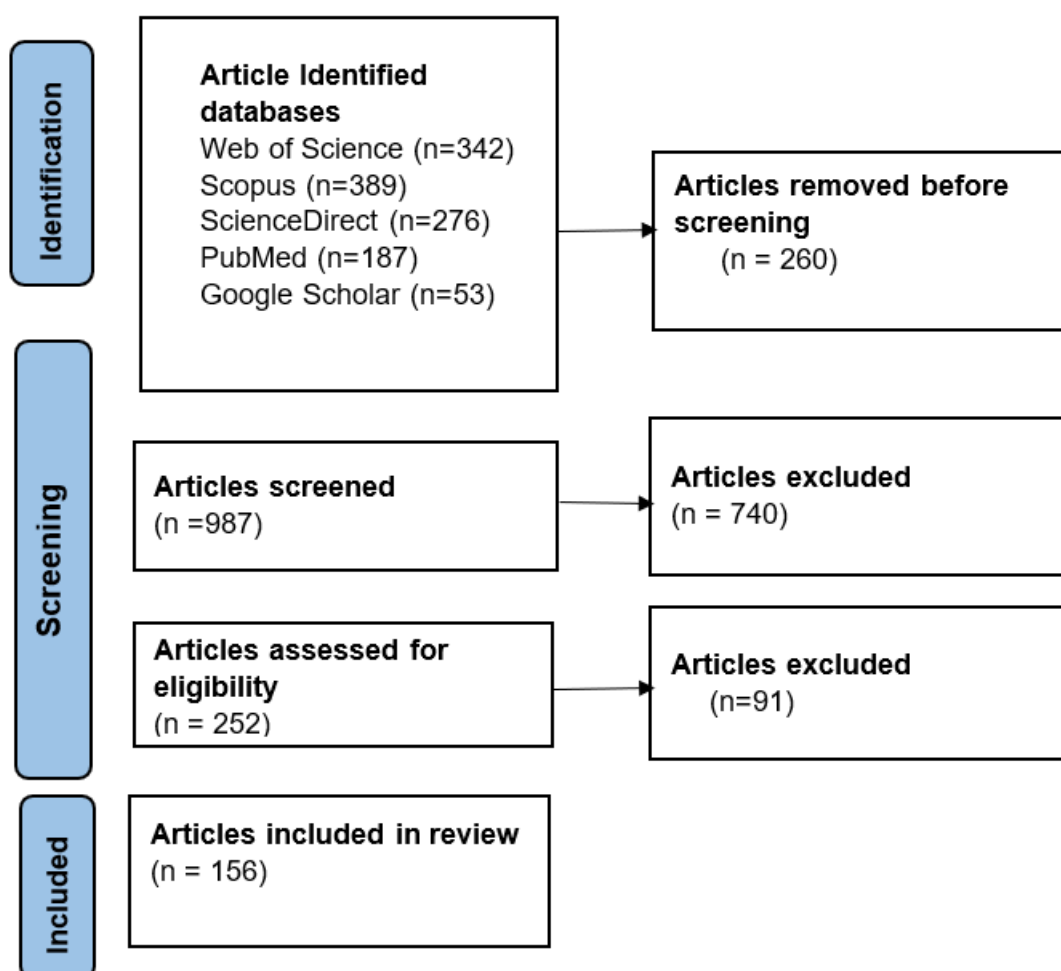
Studies had to focus on *Hermetia illucens* in the context of organic waste valorization, environmental assessment, or commercial deployment, and had to report quantitative data on processing efficiency, environmental impacts, economic performance, or operational characteristics. We included peer-reviewed articles and technical reports where methodological detail was sufficient for quality appraisal.

### 3.4 Study Selection Process

The search returned 1,247 records. After removing duplicates in Covidence (Veritas Health Innovation, 2023), 987 unique records remained for screening. Two reviewers independently screened titles and abstracts, following

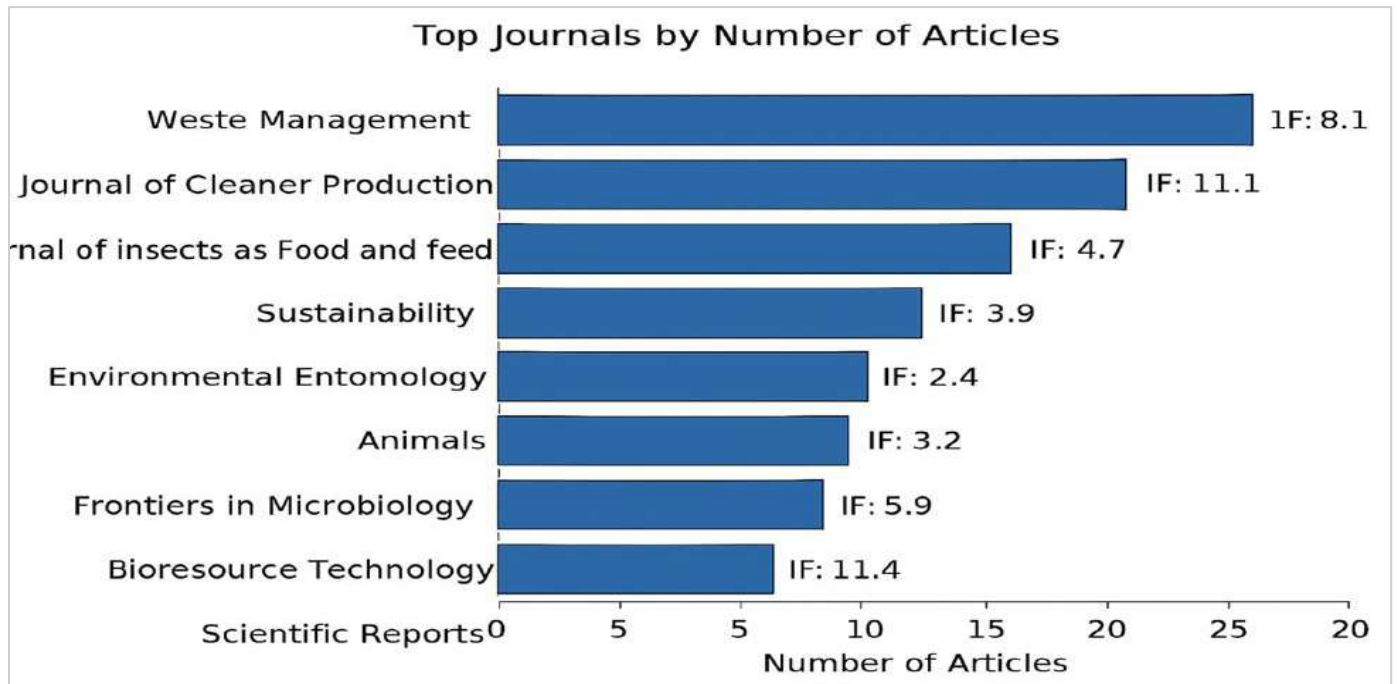
standard practice for reducing subjective bias (Higgins & Green, 2008). Disagreements were resolved by discussion; a third reviewer was consulted when needed.

Full-text assessment was conducted on 247 articles. We examined methodological quality, data completeness, and fit with the inclusion criteria. Of these, 156 met requirements and entered the final synthesis. Most full-text exclusions stemmed from insufficient quantitative data, poor methodological quality, focus outside organic waste applications, or duplicated datasets. The selection procedure is summarized in Figure 1.



**Figure 1**  
PRISMA Flow Diagram of Study Selection

The included studies were distributed across 61 peer reviewed journals, reflecting the interdisciplinary character of research on black soldier fly systems. Publication outlets covered fields such as waste management, environmental science, entomology, biotechnology, and agricultural systems. A notable share of studies appeared in journals including *Waste Management*, *Journal of Cleaner Production*, and *Bioresourc e Technology*, which frequently publish research on resource recovery and environmental assessment. This distribution illustrates that scholarship on black soldier fly bioconversion is situated at the intersection of environmental engineering, biological sciences, and sustainability research. The breadth of journal representation suggests that the search strategy successfully captured literature across multiple disciplinary domains, as illustrated in **Figure 2**.



**Figure 2**

*Distribution of BSF Research Articles across Top Journals (n=156 studies). Impact Factors (2023) Shown for Each Journal Indicate Publication in High-Quality Outlets*

### 3.5 Data Extraction

Data extraction followed a structured and piloted template developed prior to full review. The template captured bibliographic information, study design characteristics, substrate type, operational scale, treatment duration, system specifications, environmental performance indicators, economic metrics, and methodological quality features. The research team refined the template after preliminary screening to ensure consistency across diverse study designs. Two reviewers independently extracted data from all included studies. Extracted information was compared and reconciled through discussion until agreement was reached. When essential data were unclear or incomplete, corresponding authors were contacted. Responses were received for 23 studies, representing approximately two thirds of those contacted, and additional information was incorporated into the final dataset where appropriate.

### 3.6 Mixed Methods Integration

This review combined quantitative synthesis with qualitative interpretation in order to capture both measurable performance outcomes and contextual dimensions of implementation. Integration followed principles described in mixed methods scholarship (Huyler & McGill, 2019), although the present study does not involve primary data collection. Quantitative synthesis focused on environmental and performance indicators reported across studies. Effect sizes were aggregated using random effects models to account for expected variability in substrates, operational scale, and geographic context. Statistical analysis was conducted in R version 4.3.1 using established meta analytic packages (Viechtbauer, 2010; Liu & Zuo, 2015). Study heterogeneity was evaluated using Cochran's Q and the  $I^2$  statistic, with interpretation guided according to conventional thresholds (Higgins et al., 2003). Rather than assuming uniform treatment effects, the analysis emphasized variability across contexts.

#### 3.6.1 Thematic Analysis

Qualitative evidence relating to implementation conditions, regulatory environments, and operational challenges was examined using reflexive thematic analysis following the approach outlined in Braun and Clarke (2006). NVivo 14 software facilitated coding and organization of textual data (Lumivero, 2023). An initial codebook was developed through independent reading of a subset of studies, after which coding consistency was assessed. Agreement levels were considered satisfactory before proceeding to full coding. Through iterative review and discussion, the analysis identified eight overarching themes related to technological scalability, regulatory context, economic viability, environmental implications, social acceptance, knowledge transfer, infrastructure requirements, and market development patterns. Themes were refined through repeated comparison across studies rather than imposed deductively.



### 3.7 Quality Assessment and Risk of Bias

Quality appraisal was conducted using established tools appropriate to study design. Observational studies were assessed using the Newcastle Ottawa Scale (Wells et al., 2000). Animal studies were examined using the SYRCLE risk of bias tool (Hooijmans et al., 2014). Qualitative research reporting was evaluated using COREQ criteria (Tong et al., 2007). Where studies included mixed designs, appraisal criteria were applied proportionate to the dominant methodology. Publication bias was explored using funnel plot inspection and Egger's regression test, with statistical interpretation informed through established guidance (Jin et al., 2015). Sensitivity analysis was conducted to examine the influence of study quality and design variation on pooled estimates. Quality assessment results were considered during interpretation rather than used mechanically as exclusion criteria except where methodological flaws compromised data reliability.

### 3.8 Data Synthesis and Integration

Quantitative and qualitative findings were integrated during interpretation rather than treated as parallel outputs. Patterns of convergence across environmental performance, economic metrics, and regulatory context were examined to identify consistent findings. Where divergence occurred, contextual explanations were explored, particularly in relation to geographic location, operational scale, and substrate type. Sensitivity analyses examined the influence of study characteristics on pooled environmental outcomes. To reduce inflation of Type I error across multiple comparisons, adjusted significance thresholds were applied where appropriate. Integration emphasized explanatory coherence rather than statistical dominance, consistent with guidance in mixed methods integration literature (Fetters & Molina Azorin, 2017).

### 3.9 Limitations and Mitigation

Several methodological limitations warrant consideration. First, publication bias may favor studies reporting positive environmental or economic outcomes. Second, geographic concentration of research in Europe and North America limits generalizability. Third, life cycle assessments vary in system boundaries, allocation methods, and energy assumptions, complicating direct comparison. Finally, long term operational data remain limited in several regions. To address these constraints, the review incorporated grey literature where methodological transparency permitted evaluation. Contact with researchers and industry practitioners supplemented incomplete datasets. Standardized effect size metrics were applied to enhance comparability across studies. Heterogeneity and uncertainty were reported transparently and interpreted cautiously rather than minimized.

## IV. FINDINGS & DISCUSSION

### 4.1 Findings

#### 4.1.1 BSF Waste Processing Capabilities and Efficiency

A total of 156 studies reported data on substrate processing performance. Bioconversion ratios differed across substrate categories, with statistically significant variation observed across feedstock types ( $F = 45.3$ ,  $p < 0.001$ ). Food waste showed a mean bioconversion ratio of  $51.3 \pm 8.7$  percent and mean waste reduction of  $95.0 \pm 3.2$  percent. Palm oil waste recorded a mean bioconversion ratio of  $13.3 \pm 3.6$  percent and mean waste reduction of  $68.4 \pm 8.9$  percent. Feed conversion ratios ranged from  $2.51 \pm 0.84$  for food waste to  $9.84 \pm 2.87$  for palm oil waste. Processing time ranged from 12 to 26 days across all substrates, with an overall mean of  $16.8 \pm 3.2$  days. Overall waste reduction across all studies averaged  $82.3 \pm 10.1$  percent. Detailed substrate specific values are presented in Table 1.

**Table 1**

*Summary Statistics of BSF Waste Processing Performance Across Different Substrates (n=156 studies)*

Substrate Type	n	Bioconversion Ratio (%)	Waste Reduction (%)	FCR	Processing Time (days)
		Mean $\pm$ SD (Range)	Mean $\pm$ SD (Range)	Mean $\pm$ SD (Range)	Mean $\pm$ SD (Range)
Food waste	48	$51.3 \pm 8.7$ (35.2-68.4)	$95.0 \pm 3.2$ (87.3-98.6)	$2.51 \pm 0.84$ (1.5-4.2)	$14.2 \pm 2.1$ (12-18)
Fruit/vegetable	32	$42.8 \pm 6.4$ (28.6-55.1)	$89.2 \pm 4.5$ (78.4-94.7)	$3.42 \pm 1.12$ (2.1-5.8)	$15.8 \pm 2.4$ (13-20)
Poultry manure	27	$28.6 \pm 5.3$ (18.4-37.2)	$78.3 \pm 6.8$ (65.2-86.4)	$5.86 \pm 1.95$ (3.8-9.2)	$18.4 \pm 2.7$ (15-23)
Dairy manure	19	$22.4 \pm 4.8$ (13.3-29.5)	$72.8 \pm 7.2$ (58.6-81.3)	$7.23 \pm 2.34$ (4.5-11.8)	$19.7 \pm 3.1$ (16-25)
Palm oil waste	15	$13.3 \pm 3.6$ (8.2-18.7)	$68.4 \pm 8.9$ (52.3-78.6)	$9.84 \pm 2.87$ (6.2-14.5)	$20.3 \pm 2.9$ (17-26)
Mixed waste	15	$35.7 \pm 7.2$ (24.3-46.8)	$82.6 \pm 5.4$ (71.2-89.3)	$4.15 \pm 1.38$ (2.8-6.9)	$16.5 \pm 2.3$ (14-21)
<b>Overall</b>	<b>156</b>	<b><math>35.4 \pm 14.2</math> (8.2-68.4)</b>	<b><math>82.3 \pm 10.1</math> (52.3-98.6)</b>	<b><math>4.87 \pm 2.76</math> (1.5-14.5)</b>	<b><math>16.8 \pm 3.2</math> (12-26)</b>

*Note:* FCR = Feed Conversion Ratio (kg substrate/kg larvae biomass)



#### 4.1.2 Environmental Impact Assessment

Life cycle assessment data were reported in 23 studies. Mean global warming potential for black soldier fly treatment was  $168 \pm 86$  kg CO<sub>2</sub> eq per ton of waste (95 percent confidence interval: 131 to 205). Composting reported  $790 \pm 195$  kg CO<sub>2</sub> eq per ton, landfilling reported  $1,350 \pm 150$  kg CO<sub>2</sub> eq per ton, and incineration reported  $1,000 \pm 100$  kg CO<sub>2</sub> eq per ton.

Reported reductions relative to composting included 62 percent lower direct CO<sub>2</sub> emissions, 87 percent lower methane emissions, and 95 percent lower nitrous oxide emissions. Under specified system configurations incorporating renewable energy inputs and substitution accounting, reported values reached  $-432$  kg CO<sub>2</sub> eq per ton. Meta analytic estimation yielded Hedges'  $g = -2.84$  (95 percent confidence interval:  $-3.21$  to  $-2.47$ ) for greenhouse gas reduction. Heterogeneity was high ( $I^2 = 78.4$  percent). Waste volume reduction yielded Hedges'  $g = 3.21$  with comparable heterogeneity levels. Egger's regression test did not detect significant publication bias for primary outcomes ( $p > 0.05$ ). Summary results are presented in Table 2.

**Table 2**

*Meta-Analysis of Environmental Impact Studies*

Impact Category	Number of Studies	Effect Size (Hedges' g)	95% Confidence Interval	I <sup>2</sup> (%)	Egger's Test (p-value)
GHG Reduction	23	-2.84	-3.21 to -2.47	78.4	0.082
Energy Efficiency	18	-1.62	-1.95 to -1.29	65.2	0.134
Waste Volume Reduction	34	3.21	2.88 to 3.54	82.6	0.056
Water Usage	12	-0.84	-1.18 to -0.50	45.3	0.241
Land Use	9	-2.15	-2.62 to -1.68	58.7	0.168

**Note:** Negative effect sizes indicate reduction relative to conventional waste management methods.  $I^2$  represents between study heterogeneity.

#### 4.1.3 Economic Performance Across Operational Scales

Economic performance data were reported across multiple operational scales. Capital investment requirements differed according to facility capacity. Initial capital expenditure per ton of processing capacity averaged  $125,000 \pm 35,000$  USD for small scale systems,  $85,000 \pm 22,000$  USD for medium scale systems, and  $45,000 \pm 12,000$  USD for large scale systems. Operating cost parameters showed scale related variation. Energy costs per ton of waste averaged  $28.5 \pm 8.2$  USD for small scale systems,  $22.3 \pm 6.4$  USD for medium scale systems, and  $15.7 \pm 4.8$  USD for large scale systems. Labor costs per ton of waste averaged  $45.2 \pm 12.3$  USD for small scale systems,  $25.4 \pm 7.8$  USD for medium scale systems, and  $12.8 \pm 3.9$  USD for large scale systems.

Financial performance metrics were reported in terms of gross margin, payback period, and internal rate of return. Gross margin averaged  $32.4 \pm 8.7$  percent for small scale systems,  $42.8 \pm 7.2$  percent for medium scale systems, and  $51.3 \pm 6.4$  percent for large scale systems. Mean payback period was  $5.8 \pm 1.4$  years for small scale systems,  $4.2 \pm 1.1$  years for medium scale systems, and  $3.1 \pm 0.8$  years for large scale systems. Internal rate of return averaged  $18.4 \pm 5.2$  percent for small scale systems,  $24.7 \pm 4.8$  percent for medium scale systems, and  $31.2 \pm 4.3$  percent for large scale systems. Detailed economic parameters across scale categories are presented in Table 3.

**Table 3**

*Economic Analysis of BSF Production Systems*

Economic Parameter	Small Scale (<10 tons/day)	Medium Scale (10-50 tons/day)	Large Scale (>50 tons/day)
	Mean $\pm$ SD (Range)	Mean $\pm$ SD (Range)	Mean $\pm$ SD (Range)
<b>Capital Investment</b>			
Initial CAPEX (\$/ton capacity)	$125,000 \pm 35,000$ (75,000-185,000)	$85,000 \pm 22,000$ (55,000-115,000)	$45,000 \pm 12,000$ (28,000-65,000)
<b>Operating Costs</b>			
Energy (\$/ton waste)	$28.5 \pm 8.2$ (18.2-42.3)	$22.3 \pm 6.4$ (14.5-32.8)	$15.7 \pm 4.8$ (9.8-22.4)
Labor (\$/ton waste)	$45.2 \pm 12.3$ (28.4-68.5)	$25.4 \pm 7.8$ (15.2-38.6)	$12.8 \pm 3.9$ (7.5-18.2)
<b>Financial Performance</b>			
Gross margin (%)	$32.4 \pm 8.7$ (18.2-45.6)	$42.8 \pm 7.2$ (28.4-54.3)	$51.3 \pm 6.4$ (38.7-62.8)
Payback period (years)	$5.8 \pm 1.4$ (3.8-8.2)	$4.2 \pm 1.1$ (2.8-6.1)	$3.1 \pm 0.8$ (2.1-4.3)
IRR (%)	$18.4 \pm 5.2$ (10.2-26.8)	$24.7 \pm 4.8$ (16.4-32.5)	$31.2 \pm 4.3$ (22.8-38.6)

#### 4.1.4 Product Quality and Nutritional Composition

Nutritional composition data were reported in 34 studies. Black soldier fly larvae meal contained  $45.2 \pm 4.8$  percent crude protein on a dry matter basis. Crude fat content averaged  $35.4 \pm 5.2$  percent, ash content averaged  $7.3 \pm$

1.4 percent, and crude fiber averaged  $7.1 \pm 1.8$  percent. Lauric acid represented  $45.8 \pm 6.3$  percent of total fatty acids. Comparative values for conventional protein sources are presented in Table 5. Fishmeal contained  $65.3 \pm 3.2$  percent crude protein, soybean meal contained  $48.1 \pm 2.4$  percent, and poultry meal contained  $58.7 \pm 4.1$  percent. Differences across protein sources were statistically significant ( $p < 0.001$ ) for crude protein, crude fat, ash, crude fiber, and lauric acid content. Reported market application distribution across studies was 45 percent aquaculture, 25 percent poultry feed, 20 percent pet food, and 10 percent other livestock applications.

**Table 4**

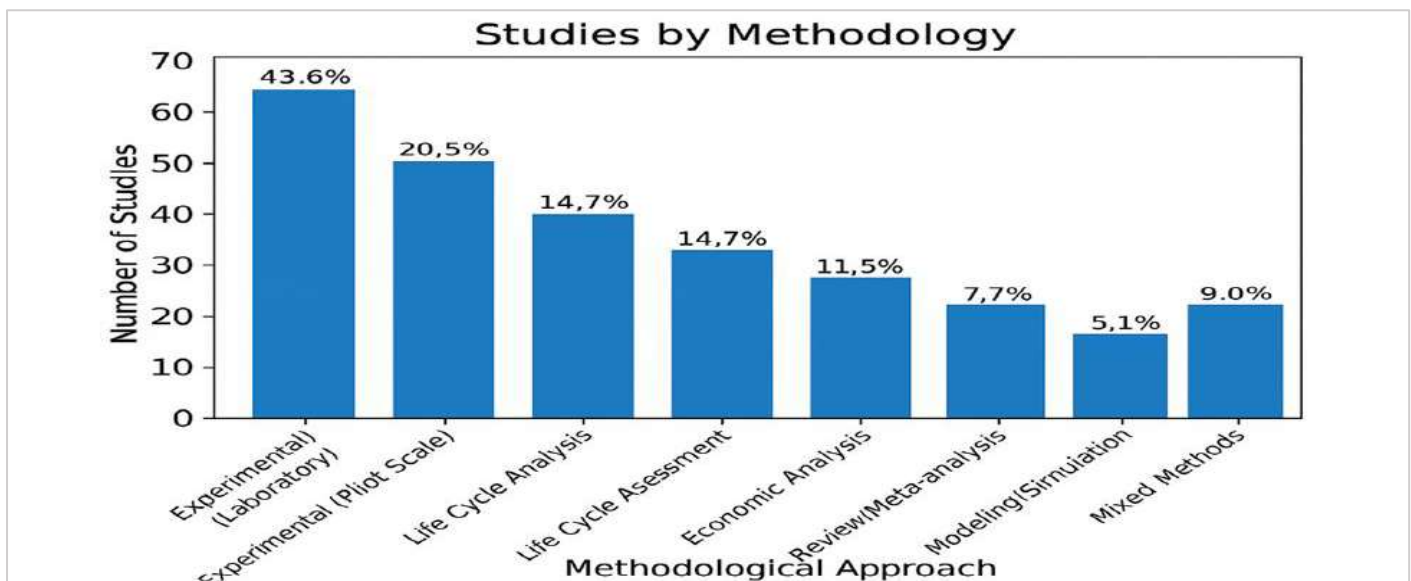
*Nutritional Composition of Black Soldier Fly Larvae Compared to Conventional Protein Sources*

Parameter	BSF Larvae (Mean $\pm$ SD)	Fishmeal (Mean $\pm$ SD)	Soybean Meal (Mean $\pm$ SD)	Poultry Meal (Mean $\pm$ SD)	p-value
Crude Protein (% DM)	$45.2 \pm 4.8$	$65.3 \pm 3.2$	$48.1 \pm 2.4$	$58.7 \pm 4.1$	<0.001
Crude Fat (% DM)	$35.4 \pm 5.2$	$10.2 \pm 2.1$	$20.3 \pm 1.8$	$12.5 \pm 2.7$	<0.001
Ash (% DM)	$7.3 \pm 1.4$	$20.1 \pm 2.8$	$6.4 \pm 0.9$	$14.3 \pm 2.2$	<0.001
Crude Fiber (% DM)	$7.1 \pm 1.8$	$1.2 \pm 0.4$	$7.2 \pm 1.1$	$2.4 \pm 0.8$	<0.001
Lauric Acid (% FA)	$45.8 \pm 6.3$	$0.2 \pm 0.1$	$0.1 \pm 0.05$	$0.3 \pm 0.1$	<0.001

Note: DM = Dry matter; FA = Fatty acids.

#### 4.1.5 Research Methodology Distribution

Among the 156 included studies, laboratory based experimental designs accounted for 43.6 percent of publications. Pilot scale experimental studies represented 20.5 percent. Life cycle analysis studies accounted for 14.7 percent. Life cycle assessment studies also accounted for 14.7 percent. Economic analyses represented 11.5 percent of publications. Review and meta-analysis studies accounted for 7.7 percent, modelling and simulation studies represented 5.1 percent, and mixed methods studies accounted for 9.0 percent. The distribution of methodological approaches is presented in Figure 5.

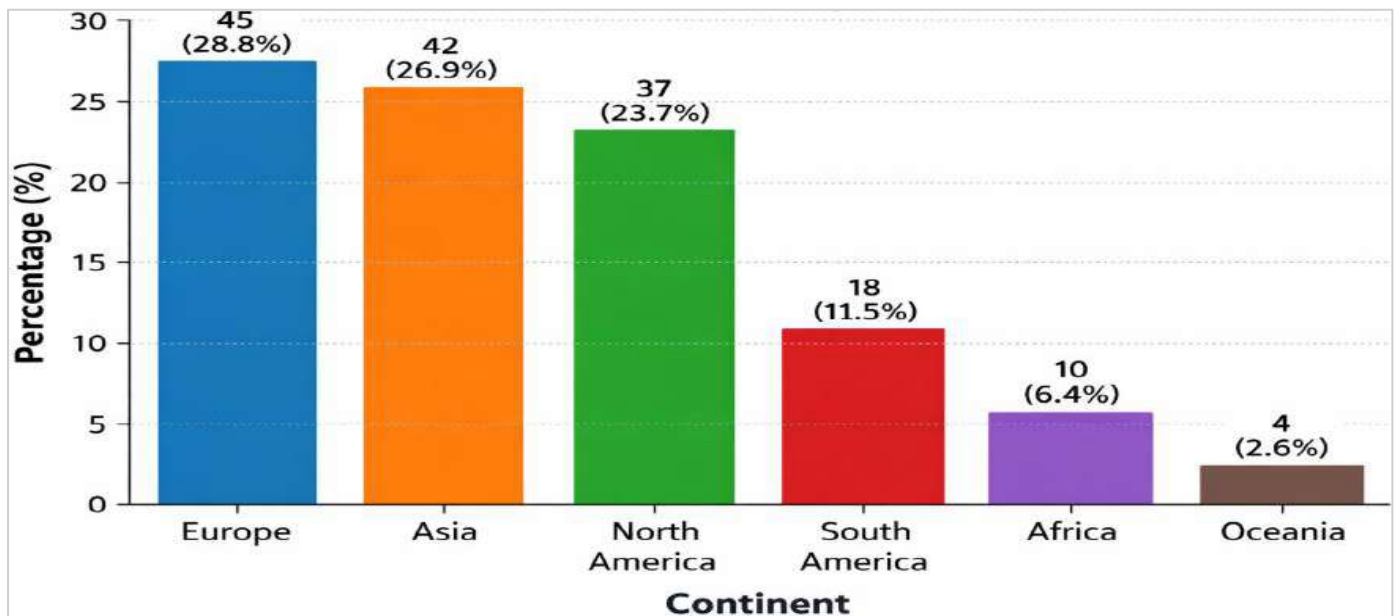
**Figure 5**

*Distribution of methodological approaches in black soldier fly research (n = 156).*

Laboratory studies account for 43.6% and pilot scale experiments 20.5%, with remaining percentages distributed across life cycle analysis, economic analysis, review, modelling, and mixed methods studies.

#### 4.1.6 Geographic Distribution

The 156 included studies were distributed across six regions. Europe accounted for 45 studies (28.8%), Asia for 42 studies (26.9%), North America for 37 studies (23.7%), South America for 18 studies (11.5%), Africa for 10 studies (6.4%), and Oceania for 4 studies (2.6%). The regional distribution is presented in Figure 6.

**Figure 6**

*Geographic Distribution of Black Soldier Fly Research Studies (n = 156).*

Percentages indicate proportion of total included studies across regions.

#### 4.1.7 Barriers and Success Factors

Thematic analysis of 47 case studies identified reported barriers and enabling factors associated with black soldier fly implementation. Technical constraints included temperature control requirements (89% of cases), substrate quality variability (76%), reproduction management challenges (68%), and disease or contamination risks (54%). Reported economic constraints included high initial capital investment (92%), energy costs for climate control (78%), market price competition (65%), and supply chain limitations (58%). Reported enabling factors included strategic partnerships (84% of successful cases), vertical integration strategies (76%), government subsidies or incentives (71%), and proximity to waste sources (68%).

#### 4.1.8 Regulatory Landscape Analysis

Regulatory frameworks were examined across 15 countries. Aquaculture approval was reported in the European Union in 2017 and poultry feed approval in 2021, limited to non-ruminant species, with substrate restrictions to vegetal and pre-consumer waste. In the United States, aquaculture approval was reported in 2018, with poultry approval varying across states. Canada reported approvals across aquaculture, poultry, and pet feed categories between 2015 and 2016. China reported approvals across multiple categories between 2018 and 2020. Reported approval timelines ranged from approximately one to two years in China to three to five years in the European Union. Regulatory characteristics are summarized in Table 6.

**Table 6**

*Regional Regulatory Frameworks for Black Soldier Fly Applications*

Region/Country	Aquaculture	Poultry	Swine	Pets	Substrate Restrictions	Approval Timeline
European Union	✓ (2017)	✓ (2021) *	✗	✓ (2017)	Vegetal only, pre-consumer	3–5 years
United States	✓ (2018)	✓ (State)†	Research	✓ (2016)	No restrictions reported	2–4 years
Canada	✓ (2016)	✓ (2016)	Research	✓ (2015)	Pre-consumer preferred	2–3 years
China	✓ (2019)	✓ (2020)	Pilot	✓ (2018)	Limited restrictions	1–2 years
Brazil	✓ (2020)	Research	✗	✓ (2019)	No animal byproducts	3–4 years

**Note:** ✓ = Approved; ✗ = Not approved; \*Limited to non-ruminants; †State level variation.



## 4.2 Discussion

### 4.2.1 Environmental Performance and Greenhouse Gas Outcomes

Our first question was straightforward: does BSF bioconversion actually reduce greenhouse gas emissions compared to conventional waste management? Across 23 life cycle assessment studies, the answer is yes, and by a considerable margin. This aligns with work on how larval digestive physiology drives efficient nutrient assimilation (Bonelli et al., 2019) and goes beyond the narrower assessments in Gonçalves Matos (2023) and Jung et al. (2022). The magnitude of reductions we found is broadly consistent with Ronda et al. (2023) and Parodi et al. (2022), though we want to stress that variation across system configurations was substantial.

The high heterogeneity ( $I^2 = 78.4\%$ ) tells us something important: environmental performance is not a fixed property of BSF technology. It depends heavily on how system boundaries are drawn, how products are allocated, what energy is used, and what conventional products are assumed to be displaced. The finding that net negative emissions are achievable under specific configurations (Mertenat et al., 2019) holds up in parts of our evidence base, especially where facilities use renewable energy and where BSF products displace carbon-intensive alternatives. But we urge caution with the pooled estimates given the methodological diversity across studies.

These results have implications for how we think about the waste hierarchy (Papargyropoulou et al., 2014). Composting is often treated as the default “green” option, but our synthesis suggests that biological valorization through insect systems deserves a place in climate policy discussions (IPCC, 2021; UNEP, 2021). Differences in scale dynamics relative to traditional systems reported in Wilson et al. (2015) are consistent with recent analyses highlighting nonlinear relationships between facility size and emissions performance in insect-based systems (Grossule & Lavagnolo, 2023; Rochimawati et al., 2025). The take-away is that blanket rankings of waste treatment pathways are unhelpful; context-specific assessment is essential (Mkilima, 2025).

### 4.2.2 Economic and Operational Feasibility

We next asked whether BSF operations are economically viable, and for whom. The short answer: it depends on scale. This echoes what has been found for resource recovery business models more broadly (Malmström et al., 2016). Unlike conventional waste treatment facilities that rely heavily on tipping fees (Hoornweg & Bhada-Tata, 2012), black soldier fly operations frequently integrate multiple revenue streams, including protein meal, oil, and soil amendments, as documented in Bruno et al. (2025) and Sibonje, Riungu and James (2024).

But profitability is uneven across regions. Tipping fees, energy costs, and compliance requirements create very different economic realities for a BSF facility in the Netherlands versus one in Cameroon or Malaysia (Cheon et al., 2022; Ghandy et al., 2025). This is a structural issue, not a technological one. As noted in Batool et al. (2024), alignment between policy incentives and environmental objectives remains central to economic viability. Early worries about consumer acceptance (Berggren et al., 2019) seem to be fading as regulations evolve and the technology matures. That said, we would caution against over-reliance on market growth projections, given how volatile feed markets are and how quickly regulatory standards are changing.

### 4.2.3 Regulatory Frameworks and Institutional Context (Objective 3)

Our regulatory analysis covered 15 countries, and the fragmentation we found was striking. Approval pathways, substrate restrictions, and permitted product categories vary enormously. The EU’s restriction to vegetal-only substrates reflects precautionary feed safety principles but shuts out potentially valuable waste streams (Halloran et al., 2018; Boatta et al., 2023). China’s faster approval timelines (Liu et al., 2023) show a different regulatory philosophy, and Canada sits somewhere in between with its risk-based approach (Lee et al., 2023). The lack of harmonized international standards complicates cross-border trade; notably, there is still no Codex Alimentarius guidance on insect-derived feed (Dobersek et al., 2023). As noted in Everitt et al. (2023), regulatory fragmentation increases compliance costs and affects scalability. In our assessment, these institutional barriers matter just as much as the technology’s environmental credentials.

### 4.2.4 Barriers and Enabling Conditions (Objective 4)

What separates the BSF facilities that succeed from those that struggle? On the technical side, temperature control, inconsistent substrate quality, and colony management challenges came up repeatedly, consistent with Klammsteiner et al. (2022). Promising solutions have emerged, including heat recovery systems and optimized facility layouts, as described in Wong et al. (2023) and Tan et al. (2022). But performance still depends heavily on where a facility is located and how its supply chain is configured (Guo et al., 2021). Among successful operations, strategic partnerships and vertical integration stood out as recurring themes, building on earlier findings about collaborative models (Veldkamp et al., 2021; Akwa et al., 2025). These patterns align with broader ecosystem perspectives on technological scaling (Ghandy et al., 2025). In developing regions, capital costs and infrastructure gaps remain the most persistent barriers (Ghandy et al., 2025).



#### 4.2.5 Research Gaps and Emerging Directions (Objective 5)

Finally, we identified several gaps that the field urgently needs to address. Genetic improvement of BSF colonies is far behind what has been achieved in conventional livestock (Khamis et al., 2022). CRISPR and other molecular tools have barely been explored for BSF (Oliveira et al., 2026), and the regulatory implications of genetically modified insect strains are almost entirely unaddressed (Vantomme & Geuens, 2023). Coupling BSF systems with aquaponics or anaerobic digestion looks promising for boosting resource efficiency (Alyokhin et al., 2018; Julita et al., 2020) but we still lack a clear understanding of how these coupled systems interact at scale. Perhaps most neglected are the social dimensions: what happens to informal waste workers when BSF facilities formalize the waste stream? What are the gender implications? (Thi et al., 2015; Nugroho et al., 2023).

#### 4.2.6 Synthesis

Taken together, BSF bioconversion sits at a crossroads of waste management, protein production, and resource recovery. The environmental case is strong under the right conditions, but economic returns and regulatory landscapes vary widely. As noted in Ojha et al. (2022) and Nikravech et al. (2022), insect-based systems are still finding their place within broader sustainability transitions. Where the field goes from here depends on whether regulators, researchers, and industry can coordinate effectively (Saatkamp et al., 2022; van Huis & Oonincx, 2017; Su et al., 2025).

## V. CONCLUSIONS & RECOMMENDATIONS

### 5.1 Conclusion

Our synthesis of 156 studies shows that BSF bioconversion can meaningfully reduce greenhouse gas emissions relative to conventional waste treatment while converting a substantial share of organic waste into usable products. But outcomes are not guaranteed. They depend on system design, energy sources, operational scale, geographic context, and regulatory environment. BSF technology is not a silver bullet for the organic waste problem, but the evidence positions it as a credible component of circular bioeconomy strategies. Realizing that potential will require better standardization in how we measure performance, greater regulatory coherence across jurisdictions, and implementation approaches tailored to local conditions.

### 5.2 Recommendations

The findings indicate that black soldier fly bioconversion can contribute to waste reduction, resource recovery, and greenhouse gas mitigation under specific operational and institutional conditions. Strengthening its role within circular bioeconomy transitions requires coordinated action across methodological, regulatory, and policy domains. Methodological standardization in life cycle assessment and economic reporting is necessary to enhance comparability across studies and reduce uncertainty associated with heterogeneous system boundaries and allocation approaches. Regulatory harmonization across jurisdictions would reduce compliance complexity, clarify substrate eligibility criteria, and facilitate cross-border trade in insect-derived feed products. Targeted policy instruments, including financial incentives, infrastructure development, and technical capacity building, may improve viability for small and medium-scale operators. Future research should prioritize long-term operational data, socio-economic implications, and integration of BSF systems within broader waste management and agricultural value chains. Collectively, these measures may support more consistent environmental and economic outcomes across contexts.

## REFERENCES

- Akwa, T. E., Tsafack, H. N., Gitau, L., & Azefack, L. T. (2025). Black soldier fly larva: A resource insect larva worth promoting in achieving sustainable development goals—A systematic review. *Sustainable Food Connect, 1*, Article 0004. <https://doi.org/10.69709/SustainFoodConn.2025.138493>
- Alyokhin, A., Buzza, A., & Beaulieu, J. (2018). Effects of food substrates and moxidectin on development of black soldier fly, *Hermetia illucens*. *Journal of Applied Entomology, 143*(10), 821–831.
- Batool, M., Tabinda, A. B., & Tahir, A. (2024). Black soldier fly larvae feed suitability for chicken and prospects for economic valuation and viability aspects. *Journal of Insects as Food and Feed, 10*(11), 1747–1767. <https://doi.org/10.1163/23524588-00001117>
- Berggren, Å., Jansson, A., & Low, M. (2019). Approaching ecological sustainability in the emerging insects-as-food industry. *Trends in Ecology & Evolution, 34*(2), 132–138. <https://doi.org/10.1016/j.tree.2018.11.005>
- Boatta, F., Smit, J. A. H., Lautenschütz, M. A. W. M., Ellen, E. D., & Ellers, J. (2023). Heritability of fat accumulation in the house fly and its implication for the selection of nutritionally tailored phenotypes. *Journal of Insects as Food and Feed, 10*(5), 825–834. <https://doi.org/10.1163/23524588-20230149>



- Bonelli, M., Bruno, D., Caccia, S., Sgambetterra, G., Cappellozza, S., Jucker, C., Tettamanti, G., & Casartelli, M. (2019). Structural and functional characterization of *Hermetia illucens* larval midgut. *Frontiers in Physiology*, *10*, 204. <https://doi.org/10.3389/fphys.2019.00204>
- Booth, A., Clarke, M., Dooley, G., Gherzi, D., Moher, D., Petticrew, M., & Stewart, L. (2012). The nuts and bolts of PROSPERO: An international prospective register of systematic reviews. *Systematic Reviews*, *1*(1), 2. <https://doi.org/10.1186/2046-4053-1-2>
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. <https://doi.org/10.1191/1478088706qp063oa>
- Bruno, D., Orlando, M., Testa, E., Carnevale Miino, M., Pesaro, G., Miceli, M., Pollegioni, L., Barbera, V., Fasoli, E., Draghi, L., Baltrocchi, A. P. D., Ferronato, N., Seri, R., Maggi, E., Caccia, S., Casartelli, M., Molla, G., Galimberti, M. S., Torretta, V., Vezzulli, A., ... Tettamanti, G. (2025). Valorization of organic waste through black soldier fly: On the way of a real circular bioeconomy process. *Waste Management*, *191*, 123–134. <https://doi.org/10.1016/j.wasman.2024.10.030>
- Cheon, D. A., Jang, T., & Lee, K. P. (2022). Visualising the nutritional performance landscapes for the black soldier fly, *Hermetia illucens* (Diptera: Stratiomyidae). *Journal of Insects as Food and Feed*, *8*(5), 481-494. <https://doi.org/10.3920/JIFF2021.0131>
- Dobersek, U., Teel, K., Altmeyer, S., Adkins, J., Wy, G., & Peak, J. (2023). Meat and mental health: A meta-analysis of meat consumption, depression, and anxiety. *Critical Reviews in Food Science and Nutrition*, *63*(19), 3556–3573. <https://doi.org/10.1080/10408398.2021.1974336>
- Everitt, H., van der Werf, P., Seabrook, J. A., et al. (2023). The proof is in the pudding: Using a randomized controlled trial to evaluate the long-term effectiveness of a household food waste reduction intervention during the COVID-19 pandemic. *Circular Economy and Sustainability*, *3*, 881–898. <https://doi.org/10.1007/s43615-022-00193-7>
- Fetters, M. D., & Molina-Azorin, J. F. (2017). The Journal of Mixed Methods Research starts a new decade: The mixed methods research integration trilogy and its dimensions. *Journal of Mixed Methods Research*, *11*(3), 291-307.
- Ghandy, A., Koen, E., & Gumilang, A. (2025). Financial feasibility analysis of black soldier fly (*Hermetia illucens*) cultivation business in Bogor, West Java. *Proceeding International Seminar of Science and Technology*, *4*, 127–138. <https://doi.org/10.33830/isst.v4i1.5240>
- Gonçalves Matos, P. (2023). Critical analysis of the use of black soldier fly larvae for domestic organic waste treatment (Undergraduate thesis, Federal University of Rio de Janeiro). *ResearchGate*. <https://doi.org/10.13140/RG.2.2.18406.19520>
- Grossule, V., Fang, D., & Lavagnolo, M. C. (2023). Treatment of wastewater using black soldier fly larvae: Effect of organic concentration and load. *Journal of Environmental Management*, *338*, 117775. <https://doi.org/10.1016/j.jenvman.2023.117775>
- Guo, H., Jiang, C., Zhang, Z., Lu, W., & Wang, H. (2021). Material flow analysis and life cycle assessment of food waste bioconversion by black soldier fly larvae (*Hermetia illucens* L.). *Science of the Total Environment*, *750*, 141656. <https://doi.org/10.1016/j.scitotenv.2020.141656>
- Gusenbauer, M., & Haddaway, N. R. (2020). Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. *Research Synthesis Methods*, *11*(2), 181-217. <https://doi.org/10.1002/jrsm.1378>
- Halloran, A., Flore, R., Vantomme, P., & Roos, N. (Eds.). (2018). *Edible insects in sustainable food systems*. Springer Cham. <https://doi.org/10.1007/978-3-319-74011-9>
- Higgins, J. P. T., & Green, S. (Eds.). (2008). *Cochrane handbook for systematic reviews of interventions* (Version 5.0.0, updated February 2008). The Cochrane Collaboration.
- Higgins, J. P. T., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *BMJ*, *327*(7414), 557–560.
- Hooijmans, C. R., Rovers, M. M., de Vries, R. B., Leenaars, M., Ritskes-Hoitinga, M., & Langendam, M. W. (2014). SYRCLE's risk of bias tool for animal studies. *BMC Medical Research Methodology*, *14*(1), 43. <https://doi.org/10.1186/1471-2288-14-43>
- Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: A global review of solid waste management. *World Bank Urban Development Series Knowledge Papers*, *15*, 1-116. <https://openknowledge.worldbank.org/handle/10986/17388>
- Huyler, D., & McGill, C. M. (2019). Book review: Research design: Qualitative, quantitative, and mixed methods approaches. *New Horizons in Adult Education and Human Resource Development*, *31*(3), 75-77.
- IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- Jin, Z.-C., Zhou, X.-H., & He, J. (2015). Statistical methods for dealing with publication bias in meta-analysis. *Statistics in Medicine*, *34*(2), 343–360. <https://doi.org/10.1002/sim.6342>



- Julita, U., Fatimah, S., Suryani, Y., Kinasih, I., & Permana, A. (2020). Bioconversion of food waste by black soldier fly, *Hermetia illucens* larvae (Diptera: Stratiomyidae L.) for alternative animal feed stock. *EAI Endorsed Transactions on Energy Web*, 7(29), Article 2297613. <https://doi.org/10.4108/eai.11-7-2019.2297613>
- Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). What a waste 2.0: A global snapshot of solid waste management to 2050. *Urban Development. World Bank*. <https://doi.org/10.1596/978-1-4648-1329-0>
- Khamis, F. M., Ombura, F. L. O., Akutse, K. S., Subramanian, S., Mohamed, S. A., Fiaboe, K. K. M., Saijuntha, W., Van Loon, J. J. A., Dicke, M., Dubois, T., Ekesi, S., & Tanga, C. M. (2020). Insights in the global genetics and gut microbiome of black soldier fly, *Hermetia illucens*: Implications for animal feed safety control. *Frontiers in Microbiology*, 11, 1538. <https://doi.org/10.3389/fmicb.2020.01538>
- Lee, J. J. Y., Lim, J. W., Wong, C. Y., Tan, G. Y. A., Kuan, G., Chong, C. S., & Chang, W. S. (2023). Economic, environmental and nutritional analysis of black soldier fly larvae production using food waste: A case study in Malaysia. *Journal of Cleaner Production*, 397, 136580. <https://doi.org/10.1016/j.jclepro.2023.136580>
- Liu, X., & Zuo, Y. (2015). CompPD: A MATLAB package for computing projection depth. *Journal of Statistical Software*, 65(2), 1–21. <https://doi.org/10.18637/jss.v065.i02>
- Liu, X., Wang, X., Chen, H., Feng, H., & Yang, Q. (2023). Efficiency and nutritional quality of black soldier fly bioconversion of mixed waste: The effects of waste composition. *Science of The Total Environment*, 872, 161773. <https://doi.org/10.1016/j.scitotenv.2023.161773>
- Lumivero. (2023). NVivo qualitative data analysis software (Version 14). <https://lumivero.com/products/nvivo/>
- Malmström, A., Birge, T., Kentala-Lehtonen, J., Korhonen-Kurki, K., Pietikäinen, J., Saikku, L., & Schösler, H. (2016). Transition towards circular economy in the food system. *Sustainability*, 8(1), 69. <https://doi.org/10.3390/su8010069>
- Mertenat, A., Diener, S., & Zurbrugg, C. (2019). Black soldier fly biowaste treatment--Assessment of global warming potential. *Waste Management*, 84, 173-181. <https://doi.org/10.1016/j.wasman.2018.11.040>
- Mkilima, T. (2025). Harnessing black soldier fly larvae for sustainable waste valorisation: Advances, challenges, and biotechnological innovations. *Waste Biomass Valor.* <https://doi.org/10.1007/s12649-025-03372-3>
- Nikravech, M., Rumpold, B., Almeida Costa, A. I., Zanolli, R., & Langen, N. (2022). Consumer acceptance of insect-based food and feed products (Report No. D1.4). *Technische Universität Berlin*.
- Nugroho, R. A., Rofiq, M. N., Santoso, A. D., Yanuar, A. I., Hanifa, R., & Nadirah, N. (2023). Bioconversion of biowaste by black soldier fly larvae (*Hermetia illucens* L.) for dried larvae production: A life cycle assessment and environmental impact analysis. *F1000Research*, 12, 814. <https://doi.org/10.12688/f1000research.132371.1>
- Ojha, S., Bußler, S., & Schlüter, O. K. (2020). Food waste valorisation and circular economy concepts in insect production and processing. *Waste Management*, 118, 600–609. <https://doi.org/10.1016/j.wasman.2020.09.010>
- Oliveira, J., Guilgur, L. G., Assunção, R., Murta, D., & Trindade, A. (2026). Genomic insights and bioconversion potential in the black soldier fly (*Hermetia illucens*): Current advances and future directions. *Insects*, 17(1), 70. <https://doi.org/10.3390/insects17010070>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. <https://doi.org/10.1136/bmj.n71>
- Papargyropoulou, E., Lozano, R., Steinberger, J. K., Wright, N., & bin Ujang, Z. (2014). The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production*, 76, 106-115. <https://doi.org/10.1016/j.jclepro.2014.04.020>
- 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. (2021). Bioconversion efficiencies, greenhouse gas and ammonia emissions during black soldier fly rearing - A mass balance approach. *Journal of Cleaner Production*, 271, 122488. <https://doi.org/10.1016/j.jclepro.2020.122488>
- Parodi, A., Gerrits, W. J. J., van Loon, J. J. A., de Boer, I. J. M., Aarnink, A. J. A., & van Zanten, H. H. E. (2022). Black soldier fly rearing on pig manure: A life cycle assessment. *Journal of Cleaner Production*, 338, 130532. <https://doi.org/10.1016/j.jclepro.2022.130532>
- Rochimawati, R. N., Yuwono, A., Jayanegara, A., & Sintawardani, N. (2025). Insect's bioconversion of organic waste: A systematic literature review and bibliometric analysis. *Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan*, 15, 493. <https://doi.org/10.29244/jpsl.15.3.493>
- Ronda, A., Haro, P., & Gómez-Barea, A. (2023). Sustainability assessment of alternative waste-to-energy technologies for the management of sewage sludge. *Waste Management*, 159, 52–62. <https://doi.org/10.1016/j.wasman.2023.01.025>
- Saatkamp, H. W., Aartsma, Y., Hogeveen, H., Augustijn, M., Baumann, A., Beukeboom, L. W., ... Dicke, M. (2022). Development of sustainable business models for insect-fed poultry production: Opportunities and risks. *Journal of Insects as Food and Feed*, 8(12), 1469-1484. <https://doi.org/10.3920/JIFF2021.0216>



- Sibonje, J., Riungu, J., & James, K. (2024). The bioconversion of faecal and kitchen waste using black soldier fly larvae (*Hermetia illucens*): Mass balance process. *African Journal of Science, Technology and Social Sciences*, 2(2), 19–29. <https://doi.org/10.58506/ajstss.v2i2.163>
- Su, H., Zhang, B., Shi, J., He, S., Dai, S., Zhao, Z., Wu, D., & Li, J. (2025). Black soldier fly larvae as a novel protein feed resource promoting circular economy in agriculture. *Insects*, 16(8), 830. <https://doi.org/10.3390/insects16080830>
- Thi, N. B. D., Kumar, G., & Lin, C.-Y. (2015). An overview of food waste management in developing countries: Current status and future perspective. *Journal of Environmental Management*, 157, 220–229. <https://doi.org/10.1016/j.jenvman.2015.04.022>
- Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care*, 19(6), 349–357. <https://doi.org/10.1093/intqhc/mzm042>
- UNEP. (2021). *Food waste index report 2021*. United Nations Environment Programme. <https://www.unep.org/resources/report/unep-food-waste-index-report-2021>
- van Huis, A. (2020). Insects as food and feed, a new emerging agricultural sector: A review. *Journal of Insects as Food and Feed*, 6(1), 27–44. <https://doi.org/10.3920/JIFF2019.0017>
- van Huis, A., & Oonincx, D. G. A. B. (2017). The environmental sustainability of insects as food and feed: A review. *Agronomy for Sustainable Development*, 37, 43. <https://doi.org/10.1007/s13593-017-0452-8>
- Veldkamp, T., van Rozen, K., Elissen, H., van Wikselaar, P., & van der Weide, R. (2021). Bioconversion of digestate, pig manure and vegetal residue based waste operated by black soldier fly larvae, *Hermetia illucens* L. (Diptera: Stratiomyidae). *Animals*, 11(11), 3082. <https://doi.org/10.3390/ani11113082>
- Veritas Health Innovation. (2023). *Covidence systematic review software*. [www.covidence.org](http://www.covidence.org)
- Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, 36(3), 1–48. <https://doi.org/10.18637/jss.v036.i03>
- Wells, G. A., Shea, B., O'Connell, D., Peterson, J., Welch, V., Losos, M., & Tugwell, P. (2000). The Newcastle Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. *Ottawa Hospital Research Institute*. [http://www.ohri.ca/programs/clinical\\_epidemiology/oxford.asp](http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp)
- Wilson, D. C., Rodic, L., Modak, P., Soos, R., Carpintero Rogero, A., Velis, C., Iyer, M., & Simonett, O. (Eds.). (2015). *Global waste management outlook*. United Nations Environment Programme. <https://www.unep.org/resources/report/global-waste-management-outlook>
- Wong, C. Y., Rosli, S. S., Uemura, Y., Ho, Y. C., Leejeerajumnean, A., Kiatkittipong, W., Cheng, C. K., Lam, M. K., & Lim, J. W. (2023). Potential of black soldier fly larvae in sustainable aquaculture and agriculture: A comprehensive review. *Aquaculture International*, 31(2), 741–793. <https://doi.org/10.1007/s10499-022-01011-5>
- Wong, C. Y., Rosli, S. S., Uemura, Y., Ho, Y. C., Leejeerajumnean, A., Kiatkittipong, W., Cheng, C. K., Lam, M. K., & Lim, J. W. (2019). Potential protein and biodiesel sources from black soldier fly larvae: Insights of larval harvesting instar and fermented feeding medium. *Energies*, 12, 1570. <https://doi.org/10.3390/en12081570>