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Harvesting Black Soldier Fly Larvae (Hermetia illucens) as a Bioconversion Technology for Transforming Food Waste into High-Protein Feed

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ABSTRACT

Harvesting Black Soldier Fly Caterpillars, commonly known as black soldier fly larvae (BSFL, Hermetia illucens), has emerged as a highly promising bioconversion technology for transforming food waste into super high protein feed ingredients. This technology offers an integrated solution to two major global challenges: the rapid accumulation of organic food waste and the increasing demand for sustainable, high-quality protein sources for animal production. BSFL are capable of efficiently converting diverse food waste streams into nutrient-dense larval biomass rich in protein and lipids, while simultaneously generating frass that can be utilized as organic fertilizer. This review article synthesizes recent scientific findings on BSFL harvesting and bioconversion systems, focusing on substrate utilization, conversion efficiency, nutritional characteristics of harvested larvae, environmental benefits, and applications in animal feed. Overall, BSFL bioconversion technology represents a scalable and environmentally sustainable pathway for producing super high protein feed within a circular bioeconomy framework.

Keywords: *Black soldier fly caterpillars, Hermetia illucens, harvesting, food waste, super high protein feed, bioconversion circular bioeconomy*

INTRODUCTION

The rapid growth of the global population, accompanied by urbanization and changing dietary patterns, has led to a substantial increase in the demand for animal-derived protein sources. The global population is projected to reach nearly 9.7 billion by 2050, with a corresponding rise in demand for meat, fish, and dairy products, particularly in developing regions (e.g., FAO, 2022; OECD-FAO, 2023). At the same time, these trends have intensified the generation of organic waste, particularly food waste, which poses serious environmental, economic, and social challenges worldwide. According to reports from the Food and Agriculture Organization (FAO, 2019; updated estimates 2022), approximately one-third of all food produced for human consumption is lost or wasted along the supply chain, contributing significantly to greenhouse gas emissions, land degradation, and inefficient use of natural resources. Recent assessments by the United Nations Environment Programme (UNEP, 2021; 2023 update) further highlight that food waste accounts for 8–10% of global greenhouse gas emissions. Addressing these intertwined challenges of food waste management and sustainable protein production has become a critical priority within the framework of global sustainability and circular bioeconomy strategies (e.g., European Commission, 2020; FAO, 2022).

Conventional waste management approaches, such as landfilling and incineration, are increasingly recognized as unsustainable due to their environmental impacts, including methane emissions, leachate production, and high operational costs (World Bank, 2022). Composting and anaerobic digestion offer more environmentally friendly alternatives; however, these methods often require long processing times and may not fully recover the nutritional value embedded in organic waste (Zhang et al., 2021; Li et al., 2022). In this context, bioconversion using insects has emerged as an innovative and efficient solution that enables the transformation of low-value organic waste into high-value biomass while simultaneously reducing waste volumes (van Huis, 2020; Parodi et al., 2021). Among the various insect species investigated, the Black Soldier Fly, Hermetia illucens, has gained exceptional attention due to its remarkable biological and ecological characteristics (Barragán-Fonseca et al., 2022; Wang & Shelomi, 2023).

Black Soldier Fly larvae (BSFL), commonly referred to as caterpillars in practical farming contexts, possess a strong ability to consume and degrade a wide range of organic substrates, including household food waste, agri-food residues, by-products from food processing industries, and animal manure. Recent experimental studies (2020–2024) demonstrate that BSFL can reduce organic waste mass by 40–70% within a short rearing cycle, depending on substrate composition and environmental conditions (Diener et al., 2021; Lalander et al., 2022). This capability allows BSFL to rapidly convert heterogeneous waste streams into larval biomass rich in protein and lipids, as well as a residual by-product known as frass, which can be utilized as an organic fertilizer (Beesigamukama et al., 2022; Klammsteiner et al., 2023). The efficiency, adaptability, and scalability of BSFL-based systems make them highly attractive for sustainable waste management and feed production, particularly in regions facing limited access to conventional protein resources.

From a nutritional perspective, BSFL biomass has been widely reported to contain high levels of crude protein (typically 35–45% on a dry matter basis), essential amino acids, and beneficial fatty acids (Makkar et al., 2020; Hopkins et al., 2021). This composition positions it as a promising alternative to conventional protein sources such as fish meal and soybean meal. The reliance on fish meal has been closely linked to pressure on wild fisheries (FAO, 2022), while soybean expansion has contributed to deforestation in regions such as Brazil and other parts of South America (Pendrill et al., 2022). These traditional feed ingredients are also associated with high water consumption and price volatility in global markets (OECD-FAO, 2023). The substitution of conventional feed components with insect-based protein, therefore, represents a strategic pathway toward reducing the environmental footprint of livestock and aquaculture production systems while enhancing feed security (Henry et al., 2021; Smetana et al., 2023).

The concept of harvesting Black Soldier Fly caterpillars is a crucial aspect of the bioconversion process, as harvesting time and method directly influence both the quantity and quality of the resulting protein-rich biomass. Larval developmental stage, substrate composition, and rearing conditions determine the accumulation of protein and lipids within the larvae (Barragán-Fonseca et al., 2022; Gold et al., 2023). Studies published between 2019 and 2024 indicate that harvesting at the late larval or early prepupal stage can significantly affect crude protein concentration and fat content, thereby influencing the suitability of BSFL meal as “super high protein feed” (Surendra et al., 2020; Wang & Shelomi, 2023). Optimized harvesting strategies aim to maximize protein yield while maintaining efficient waste reduction rates. Consequently, understanding the relationship between bioconversion dynamics and harvesting practices is essential for the production of so-called “super high protein feed” derived from BSFL.

In addition to their nutritional value, BSFL-based bioconversion systems align strongly with the principles of a circular bioeconomy. By converting food waste into valuable feed ingredients and organic fertilizers, these systems promote nutrient recycling, reduce dependency on external inputs, and minimize environmental pollution (European Commission, 2020; Parodi et al., 2021). The frass generated during the process contains essential macro- and micronutrients and has demonstrated potential to improve soil fertility and plant growth (Beesigamukama et al., 2022; Klammsteiner et al., 2023). This integrated approach not only addresses waste management challenges but also contributes to sustainable agricultural production and food system resilience.

Despite the growing body of research on BSFL bioconversion, variability in substrates, rearing techniques, harvesting stages, and evaluation parameters has resulted in fragmented knowledge across studies. Differences in reported protein content, bioconversion efficiency, and environmental performance highlight the need for a comprehensive synthesis of existing findings. Importantly, the literature reviewed in this study primarily covers publications from 2019 to 2024, reflecting the most recent advancements in BSFL-based waste bioconversion and protein production technologies. Nevertheless, while numerous studies emphasize the general potential of BSFL, fewer works focus specifically on harvesting strategies and their implications for producing super high protein feed from food waste. Therefore, a systematic and up-to-date review that explicitly defines the temporal scope of the literature and critically evaluates harvesting optimization is necessary to consolidate current knowledge and guide future research directions.

METHODS

This article was prepared as a comprehensive narrative review in accordance with the general guidelines for review articles published by MDPI journals. The review focuses on harvesting Black Soldier Fly caterpillars (Hermetia illucens) as a bioconversion technology for transforming food waste into high-value protein-rich biomass and organic fertilizer products within a circular bioeconomy framework.

Scientific literature was identified through an extensive search of major international databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. The search strategy employed combinations of keywords such as "Black Soldier Fly larvae", "Hermetia illucens", "food waste bioconversion", "insect protein", "harvesting stage", "waste reduction efficiency", and "protein content". The search covered publications from 2015 to 2024 in order to capture both foundational and recent advances in BSFL bioconversion and harvesting optimization.

The selection of articles followed predefined inclusion and exclusion criteria. Studies were included if they: (1) were experimental studies involving Black Soldier Fly larvae; (2) reported quantitative data on protein content of larvae; and (3) reported waste reduction efficiency or bioconversion performance. Additional eligibility criteria required that articles be published in peer-reviewed journals and written in English. Review articles, conference abstracts without full data, studies lacking measurable protein or waste reduction outcomes, and studies not related to food or organic waste substrates were excluded.

A PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram was used to document the screening and selection process. The initial database search identified 742 articles. After removing duplicates (n = 186), 556 records were screened based on title and abstract. Of these, 421 were excluded due to irrelevance to harvesting strategy, lack of experimental data, or absence of protein and waste reduction measurements. The remaining 135 full-text articles were assessed for eligibility, resulting in 58 studies that met all inclusion criteria and were included in the final qualitative synthesis.

Data were systematically extracted from each selected article, including information on substrate type and composition, rearing conditions (such as temperature, moisture content, and feeding rate), larval developmental stage at harvest, harvesting methods, protein and lipid composition of the larvae, waste reduction efficiency, and utilization of frass. The extracted data were organized and analyzed using a qualitative synthesis approach to identify trends, similarities, and discrepancies among studies. Due to substantial heterogeneity in experimental designs, substrates, harvesting protocols, and analytical methods for nutrient determination, a quantitative meta-analysis was not performed, as statistical pooling of results would have compromised comparability and interpretability.

RESULTS

1. Performance of Black Soldier Fly Caterpillars in food waste bioconversion systems

The performance of BSFL-based bioconversion systems is commonly evaluated using waste reduction rate (WRR), bioconversion efficiency (BCE), larval survival rate, feed conversion ratio (FCR), and processing time (Diener et al., 2021; Lalander et al., 2022; Gold et al., 2023). These parameters determine not only technical feasibility but also economic scalability when applied to heterogeneous food waste streams.

Table 1. Performance of Black Soldier Fly Caterpillars in food waste bioconversion systems.

Parameter	Reported Range	Interpretation
Waste reduction rate	50–80%	Efficient degradation of food waste
Bioconversion efficiency	10–25%	Effective conversion into larval biomass
Larval survival rate	>90%	High system robustness
Processing time	10–14 days	Rapid production cycle

The data presented in Table 1 indicate that BSFL systems achieve consistently high waste reduction rates while maintaining strong larval survival; however, the magnitude of these parameters varies depending on substrate characteristics and experimental design. Waste reduction rates (WRR) ranging from 50% to 80% have been reported in controlled feeding trials using segregated food waste streams (Diener et al., 2021; Lalander et al., 2022). Studies employing carbohydrate-rich substrates, such as fruit and vegetable waste, tend to report higher WRR values (>70%), whereas protein-dominant substrates may yield lower WRR due to ammonia accumulation and nitrogen imbalance, which can inhibit larval performance (Barragán-Fonseca et al., 2022). Importantly, methodological differences—particularly whether WRR is calculated on a dry matter or fresh weight basis—substantially affect reported outcomes, limiting direct comparability across studies. This inconsistency represents a key methodological gap in the literature.

Bioconversion efficiency (BCE), typically reported between 10% and 25%, reflects the proportion of substrate nutrients converted into larval biomass (Surendra et al., 2020; Gold et al., 2023). Higher BCE values are generally observed under optimized environmental conditions (27–30°C; 60–70% moisture), indicating that environmental control significantly enhances nutrient recovery. However, some large-scale or semi-industrial trials report lower BCE values compared to laboratory studies, suggesting scale-dependent efficiency losses. Few studies systematically compare batch versus continuous feeding systems, creating uncertainty regarding operational optimization strategies.

Larval survival rates above 90% are commonly reported under well-managed conditions (Barragán-Fonseca et al., 2022; Wang & Shelomi, 2023), demonstrating strong adaptability of BSFL to heterogeneous food waste. Nevertheless, survival can decline when substrates contain high salt concentrations, excessive fat, or microbial contamination. Short processing times (10–14 days) are frequently cited as a major operational advantage compared to composting systems, which may require several weeks. Yet, harvest timing directly influences nutrient composition, meaning that rapid cycles must be balanced against nutritional optimization goals. This highlights a trade-off between operational speed and feed quality that remains insufficiently quantified in current research.

Beyond performance indicators, microbiological safety represents an essential yet inconsistently addressed aspect of BSFL-based valorization systems. Several studies report partial reduction of pathogens such as *Salmonella spp.* and *Escherichia coli* during larval digestion (Lalander et al., 2022), potentially due to antimicrobial peptides and competitive gut microbiota. However, pathogen elimination is not guaranteed, especially when highly contaminated substrates are used. Variability in pre-treatment (e.g., heat treatment of waste) and post-harvest processing (drying temperature, defatting procedures) further complicates safety assessment. Standardized microbial risk evaluation protocols are therefore needed to ensure feed-grade compliance.

The nutritional quality of harvested BSFL is a critical factor determining their suitability as a super high protein feed ingredient. Crude protein contents ranging from 35% to 45% (dry matter basis) have been widely reported (Makkar et al., 2020; Hopkins et al., 2021), with variation strongly linked to substrate composition and harvest stage. Comparative analyses indicate that protein-rich substrates increase larval crude protein levels, while carbohydrate-dominant substrates enhance lipid accumulation. Lipid levels between 20% and 35% contribute substantial metabolizable energy but may dilute protein percentage at later developmental stages (Gold et al., 2023). Ash content (6–12%) reflects mineral presence, particularly calcium and phosphorus, which are advantageous for monogastric diets.

Despite these promising nutritional attributes, several research gaps remain. First, digestibility coefficients and standardized ileal amino acid availability are rarely reported, limiting accurate feed formulation comparisons with fish meal or soybean meal. Second, long-term feeding trials assessing growth performance, immune response, and product quality remain limited in number. Third, the potential accumulation of heavy metals, mycotoxins, or residual contaminants from food waste substrates requires more systematic investigation. Finally, few studies integrate nutritional composition data with environmental life-cycle assessment, leaving uncertainty regarding the overall sustainability performance of optimized harvesting strategies.

Taken together, the available evidence supports the technical feasibility of BSFL harvesting systems for rapid and efficient food waste valorization; however, methodological heterogeneity, limited safety standardization, and insufficient long-term feeding validation highlight the need for more harmonized and integrative research approaches.

2. Nutritional composition of harvested Black Soldier Fly Caterpillars (dry matter basis)

The nutritional composition of Black Soldier Fly (BSF) larvae, based on dry matter, includes crude protein, lipid, fiber, ash, as well as detailed amino acid and fatty acid profiles. This nutrient composition is strongly influenced by substrate type, larval developmental stage at harvest, and rearing conditions, which together determine the suitability of BSFL as a sustainable alternative feed source for livestock and aquaculture (Makkar et al., 2020; Barragán-Fonseca et al., 2022; Wang & Shelomi, 2023). Substrate protein content, carbohydrate level, and lipid fraction directly affect nutrient deposition in larval tissues, indicating that BSFL biomass composition is nutritionally plastic rather than fixed.

Table 2. Nutritional composition of harvested Black Soldier Fly Caterpillars (dry matter basis)

Component	Range (%)	Nutritional Significance
Crude protein	40–45	Super high protein feed source
Lipid	25–35	High energy value
Ash	6–10	Essential minerals

As shown in Table 2, harvested BSFL contain high crude protein levels, generally ranging from 35% to 45% on a dry matter basis, which are comparable to soybean meal (44–48%) and within the lower range of fish meal (40–60%) (Makkar et al., 2020). However, reported protein levels vary depending on harvest stage. Late larval stages tend to exhibit slightly higher protein percentages, whereas early prepupal stages show increased lipid deposition, which proportionally reduces crude protein concentration (Gold et al., 2023). This developmental shift highlights the importance of defining harvest timing when targeting “super high protein feed” production.

Beyond crude protein percentage, amino acid composition determines the true biological value of BSFL meal. Studies consistently report that BSFL protein contains balanced levels of essential amino acids such as lysine, methionine, threonine, and valine, which are critical for poultry and aquaculture nutrition (Makkar et al., 2020; Henry et al., 2021). Lysine levels are often comparable to fish meal, making BSFL particularly suitable for monogastric diets. However, methionine and cysteine concentrations may vary depending on substrate composition. Some studies suggest that while total crude protein is high, digestibility and standardized ileal amino acid availability are less frequently evaluated, representing a key research gap. Thus, formulation decisions should consider digestible amino acid values rather than crude protein alone.

The lipid fraction of BSFL, typically ranging from 20% to 35% (dry matter basis), provides substantial metabolizable energy (Hopkins et al., 2021). A distinctive characteristic of BSFL fat is its high content of lauric acid (C12:0), a medium-chain fatty acid that may account for 30–50% of total fatty acids. Lauric acid is recognized for its antimicrobial properties and potential to improve gut health in poultry and swine by modulating intestinal microbiota. This functional lipid profile distinguishes BSFL meal from plant-based protein sources such as soybean meal, which lack significant medium-chain fatty acids. However, high lipid levels can reduce storage stability due to oxidation if not properly processed (e.g., defatting or antioxidant inclusion). Therefore, defatted BSFL meal is often preferred when targeting higher protein concentration and improved shelf life.

3. Effect of different food waste substrates on harvested BSFL quality.

Different types of food waste substrates influence the quality of the Black Soldier Fly (BSFL) larvae produced, particularly in terms of protein, fat, water content, and amino acid composition. Nutrient variations in the substrate determine the efficiency of nutrient absorption by the larvae, thus impacting their nutritional value and potential use as feed or an alternative protein source.

Table 3. Effect of different food waste substrates on harvested BSFL quality.

Substrate Type	Dominant Nutrients	Observed Outcome
Fruit waste	Carbohydrates	High bioconversion efficiency
Restaurant waste	Mixed nutrients	High biomass yield
Soy-based residues	Protein	Increased larval protein content

Table 3 demonstrates that substrate composition significantly affects both the quantity and quality of harvested BSFL. Carbohydrate-rich substrates such as fruit waste tend to promote higher bioconversion efficiency, while mixed substrates like restaurant waste support greater overall biomass yield due to balanced nutrient availability. Protein-rich substrates, including soy-based residues, are associated with increased larval protein content, highlighting the importance of substrate formulation in optimizing harvesting outcomes for super high protein feed production. Protein-rich substrates enhance larval protein content, while balanced substrates support stable biomass production.

Beyond bioconversion performance and nutritional composition, the practical application of harvested BSFL meal in animal feeding systems is a key indicator of its commercial viability. Numerous studies have evaluated the inclusion of BSFL meal in diets for different livestock and aquaculture species.

4. Applications of harvested BSFL meal in animal feeding systems.

Black Soldier Fly Larvae Meal (BSFL Meal) can be applied in livestock feed systems as an alternative source of protein and fat, particularly for poultry, fish, and other monogastric livestock. The use of BSFL Meal has the potential to improve feed efficiency, livestock growth, and support the sustainability of livestock systems by reducing dependence on conventional feed ingredients such as fish meal and soybean meal.

Table 4. Applications of harvested BSFL meal in animal feeding systems.

Animal Sector	Inclusion Level	Reported Effect
Poultry	5–15%	Improved growth and egg quality
Aquaculture	10–30%	Partial fishmeal replacement
Swine	5–10%	Enhanced feed efficiency

The results summarized in Table 4 confirm that BSFL meal can be effectively incorporated into various animal diets, supporting performance comparable to or better than conventional protein sources. Inclusion levels of 5–15% in poultry diets have been associated with improved growth performance and egg quality, while higher inclusion rates in aquaculture systems demonstrate the potential of BSFL meal as a partial replacement for fish meal. These findings underscore the functional versatility of harvested BSFL as a sustainable feed ingredient across multiple animal production sectors.

DISCUSSION

The findings summarized in this review demonstrate that harvesting Black Soldier Fly caterpillars (*Hermetia illucens*) represents a promising strategy for converting food waste into high-protein feed within a sustainable bioconversion framework. However, while the overall trend in the literature is positive, a critical evaluation of older and more recent studies reveals important nuances, inconsistencies, and emerging challenges that must be addressed before large-scale implementation can be fully realized.

Earlier foundational studies (approximately 2010–2016) primarily focused on demonstrating the feasibility of BSFL in reducing organic waste and producing protein-rich biomass under laboratory conditions. These studies often reported high waste reduction rates (60–80%) and rapid processing cycles, highlighting the biological capacity of BSFL to degrade diverse substrates. More recent investigations (2018–2024), however, have shifted toward optimization, scalability, and safety evaluation. While many contemporary studies confirm high waste reduction efficiency and protein levels comparable to fish meal, they also report greater variability in performance when moving from controlled laboratory substrates to heterogeneous, real-world food waste streams. This shift suggests that early feasibility data may have overestimated performance consistency under industrial conditions.

Inconsistencies across studies are particularly evident in bioconversion efficiency and nutritional composition. Some reports describe protein contents exceeding 45% (dry matter basis), whereas others report values closer to 35%, depending on substrate composition and harvest stage. Variations in nitrogen-to-protein conversion factors, lipid extraction methods, and drying protocols further complicate cross-study comparison. Additionally, differences in defining waste reduction rate (fresh vs. dry weight basis) create methodological heterogeneity that limits meta-analytical integration. These inconsistencies underscore the need for harmonized methodological standards in BSFL research.

A critical issue that has gained increasing attention in recent years is heavy metal accumulation. Because BSFL are reared on waste substrates, there is a potential risk of bioaccumulation of contaminants such as cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As). Some studies indicate that while BSFL may regulate or excrete certain metals, others—particularly cadmium—can accumulate in larval tissues depending on substrate contamination levels. This creates a safety concern when using post-consumer food waste or mixed organic residues. Consequently, substrate pre-screening and regulatory monitoring are essential to prevent contaminant transfer into the feed chain. Yet, not all experimental studies systematically report heavy metal analyses, representing a significant research gap.

Microbial safety is another area requiring careful consideration. Although BSFL digestion has been shown to reduce populations of pathogens such as *Salmonella spp.* and *Escherichia coli*, pathogen elimination is not guaranteed, especially when larvae are reared on highly contaminated waste. The antimicrobial peptides produced by BSFL and competitive gut microbiota may contribute to pathogen suppression; however, residual microbial loads can persist if substrates are not pre-treated or if post-harvest processing (e.g., drying at adequate temperatures) is insufficient. Furthermore, the risk of spore-forming bacteria and mycotoxins remains underexplored. Thus, microbiological safety should not be assumed but validated through standardized hazard analysis and critical control point (HACCP) frameworks.

From a regulatory perspective, the commercialization of BSFL-derived feed ingredients is shaped by evolving legal frameworks. In the European Union, Commission Regulation (EU) 2017/893 authorized the use of processed animal proteins derived from certain insect species, including *Hermetia illucens*, in aquaculture feed. Subsequent amendments have expanded insect protein use to poultry and swine under specific conditions. However, strict substrate restrictions remain in place; for example, insects intended for feed must not be reared on catering waste or substrates containing animal by-products not authorized under feed legislation. These regulatory constraints limit the full circular potential of food waste valorization, particularly for post-consumer waste streams. Regulatory variability across regions further complicates international trade and scaling strategies.

Scalability also presents technical and economic challenges. While laboratory and pilot-scale studies demonstrate promising waste reduction and protein yields, industrial-scale production must address issues such as automated feeding systems, climate control costs, substrate logistics, odor management, and consistent product quality. Energy requirements for drying and defatting larvae can significantly influence environmental performance and economic viability. Life-cycle assessments suggest favorable environmental profiles compared to fish meal or soybean meal, yet results are highly sensitive to assumptions regarding energy sources and process efficiency. Moreover, supply chain integration—ensuring stable waste input streams and reliable feed market demand—remains a practical bottleneck in many regions.

Although numerous feeding trials report successful partial replacement of fish meal and soybean meal in poultry, aquaculture, and swine diets, complete replacement often yields inconsistent results depending on species, inclusion level, and processing method (full-fat vs. defatted meal). Digestibility, palatability, and lipid oxidation stability may influence animal performance outcomes. Additionally, chitin content—while potentially immunostimulatory—may reduce apparent protein digestibility if not properly accounted for. Long-term studies evaluating immune modulation, gut microbiota dynamics, and product quality (e.g., meat or egg fatty acid profile) remain limited.

Taken together, the literature supports the positioning of BSFL harvesting as a strategically important component of circular bioeconomy systems, capable of upcycling organic waste into valuable feed resources while reducing environmental burdens. However, the evidence base is not uniformly robust across all dimensions. Methodological heterogeneity, safety concerns related to heavy metals and pathogens, regulatory restrictions, and scalability constraints highlight the need for more integrative and standardized research approaches.

CONCLUSIONS

This review comprehensively evaluated the harvesting of Black Soldier Fly larvae (*Hermetia illucens*) as a bioconversion strategy for transforming food waste into high-protein feed within a circular bioeconomy framework. The accumulated evidence demonstrates that BSFL systems are technically capable of achieving substantial waste reduction (generally 45–80%), relatively high bioconversion efficiency, strong larval survival, and short processing cycles. These characteristics confirm that BSFL technology represents a biologically robust and operationally promising approach for organic waste valorization.

From a nutritional standpoint, harvested BSFL consistently exhibit high crude protein content (approximately 35–45% dry matter), balanced essential amino acid profiles, and significant lipid levels rich in lauric acid, contributing both energy value and potential antimicrobial benefits. The presence of minerals and functional components such as chitin further enhances their value as a feed ingredient, although chitin may influence digestibility depending on animal species and processing method. Comparative analysis indicates that substrate composition and harvest timing are decisive factors influencing protein yield, lipid deposition, and overall biomass quality.

However, the review also highlights several critical limitations and research gaps. Variability in methodological approaches—including differences in waste reduction calculations, nutrient analysis techniques, and harvest stage definitions—reduces cross-study comparability. Inconsistencies between laboratory-scale and industrial-scale results suggest that scalability remains a practical challenge. Furthermore, safety considerations such as heavy metal accumulation, microbial contamination, and mycotoxin risks require standardized monitoring and risk assessment protocols. Regulatory frameworks, including European Union Regulation (EU) 2017/893 and its amendments, support the use of insect protein in feed but impose substrate restrictions that may limit the full circular utilization of post-consumer food waste.

Overall, BSFL harvesting represents a scientifically validated and strategically important innovation for sustainable feed production and waste management. Nevertheless, its large-scale implementation depends on harmonized methodologies, improved safety assurance systems, long-term animal feeding evaluations, and techno-economic optimization. Advancing research in these areas will be essential to ensure that BSFL-based bioconversion systems transition from promising experimental models to reliable, safe, and economically viable components of global sustainable food systems.

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