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COSMETIC-RELEVANT BIOACTIVITIES OF OIL EXTRACTS AND PROTEIN HYDROLYSATES FROM *Hermetia illucens* LARVAE: A COMPARATIVE REVIEW

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ABSTRACT

The cosmetic industry is increasingly interested in sustainable and natural bioactive ingredients. Black soldier fly (*Hermetia illucens*) larvae have gained attention as an alternative source due to their high bioconversion efficiency and suitability for circular economy systems. This review compares the cosmetic-relevant biological activities of oil extracts and protein hydrolysates derived from *Hermetia illucens* larvae. Evidence from recent studies shows clear functional differences between the two fractions. Larval oil, rich in lauric, oleic, linoleic, and palmitic acids, consistently demonstrates strong antimicrobial, anti-inflammatory, antioxidant, and photoprotective activities. These effects are primarily associated with fatty acid–mediated membrane disruption, enzyme inhibition (e.g., hyaluronidase and tyrosinase), oxidative stress reduction, and reinforcement of the skin barrier, supporting applications in anti-acne, barrier repair, and photoprotection. In contrast, protein hydrolysates composed of low molecular weight bioactive peptides exhibit pronounced antioxidant and cytoprotective activities, driven by radical scavenging, redox modulation, and potential peptide–enzyme interactions, indicating suitability for anti-aging and skin-protective formulations. In summary, comparative analysis indicates that *H. illucens* oil is more effective for antimicrobial and barrier-related functions, whereas protein hydrolysates are more relevant for antioxidant and cellular protection. These findings highlight the complementary cosmetic potential of lipid and protein fractions from *H. illucens* larvae as sustainable multifunctional ingredients.

Keywords: *Hermetia illucens*, bioactivities, lipid extracts, protein hydrolysates, bioactive peptides

INTRODUCTION

The cosmetic industry is increasingly oriented toward sustainable, naturally derived bioactive ingredients to meet consumer demand for environmentally responsible and multifunctional formulations. Conventional cosmetic actives and preservatives are often associated with petrochemical origins or sustainability concerns, prompting the exploration of alternative bioresources. In this context, black soldier fly (BSF) larvae have emerged as a promising and sustainable source of cosmetic ingredients due to their exceptional ability to convert organic waste into high-value biomass, aligning with circular economy principles (Gold *et al*., 2018).

BSF larvae are rich in lipids, proteins, and bioactive compounds that are relevant to cosmetic applications. The oil extracted from BSF larvae has a fatty acid profile dominated by lauric acid, frequently ranging from around 36-60 % of total fatty acids, with significant amounts of palmitic, oleic, and linoleic acids also present, making its profile comparable to coconut and palm kernel oils widely used in cosmetic formulations (Almeida *et al*., 2020). These fatty acids contribute to antimicrobial, anti-inflammatory, antioxidant, and photoprotective activities through mechanisms including microbial membrane disruption, enzyme inhibition, and reactive oxygen species scavenging. Consequently, BSF oil has shown potential for anti-acne applications, skin barrier enhancement, and UVB protection (Phongpradist *et al*., 2023).

In parallel, BSF protein hydrolysates produced via enzymatic hydrolysis contain bioactive peptides with molecular weights of approximately 14–25 kDa and exhibit strong antioxidant activity, achieving up to 72.6% free radical inhibition, as well as cytoprotective effects against oxidative stress (Firmansyah & Abduh, 2019; Abduh *et al*., 2023). Moreover, BSF larvae synthesize diverse antimicrobial peptides, such as defensins and cecropins, which display broad-spectrum antibacterial activity against Gram-positive and Gram-negative bacteria through membrane disruption and intracellular interference (Van Moll *et al*., 2022).

Comparatively, BSF lipid extracts primarily support skin barrier function and lipid-mediated bioactivities, whereas protein hydrolysates act through redox modulation and enzyme inhibition, indicating complementary rather than competitive roles. Therefore, this review aims to systematically compare the cosmetic-relevant biological activities of BSF-derived lipid extracts and protein hydrolysates, highlighting mechanistic insights, production strategies, and future perspectives for their development as sustainable, multifunctional cosmetic bioactives.

METHODOLOGY

The methodology of this article review is designed to analyse and compare the biological activities of oil extracts and protein hydrolysates from *Hermetia illucens* larvae that are relevant for cosmetic applications. A systematic literature search was conducted using the PubMed, Scopus, Web of Science, ScienceDirect, and Google Scholar databases with the keyword combination '*Hermetia illucens*' OR 'Black Soldier Fly', AND 'oil extract' OR 'protein hydrolysate', AND 'cosmetic' OR 'antioxidant' OR "antimicrobial" OR 'anti-aging'. Inclusion criteria included peer-reviewed articles in English that evaluated the biological activities of BSF larvae extracts for cosmetic applications.

From each review or experiment study, data were extracted on study of biochemical composition of larvae extracts, extraction methods, and biological activities such as antioxidant, antimicrobial, anti-aging, and other activities. A comparative analysis was conducted to compare the effectiveness of oil extracts versus hydrolysed proteins based on biochemical composition, biological activity spectrum, mechanism of action, and the potential synergy of combining the two.

RESULT AND DISCUSSION

Lipid and Protein Profile

During the growth of *Hermetia illucens* larvae, lipid levels rise substantially, increasing from approximately 13% to nearly 40% prior to the pupal stage. Lipid accumulation in the larvae is strongly influenced by the composition of the feeding substrate, with higher dietary lipid levels leading to greater lipid deposition in larval biomass (Gatlin *et al*., 2024). Lipid composition of BSF larvae shares similarities with coconut and palm kernel oil (Lai-Foenander *et al*., 2024). Research demonstrates that supercritical CO_2-extracted BSF larvae oil yields approximately 20-26% oil content, with major constituents including lauric acid, linoleic acid, oleic acid, and palmitic acid (Cruz *et al*., 2023).

Lauric acid functions as an effective antimicrobial agent and serves multiple roles in cosmetic formulations, acting as both a stabilizer and an emulsifier (Lai-Foenander *et al*., 2024). Recent investigations have shown that the fatty acid composition can be modulated through substrate selection. When BSF larvae are fed olive pomace, the resulting oil exhibits an elevated oleic acid content, demonstrating a diet-dependent modification of the lipid profile (Santos Filipe *et al*., 2024).

BSF larvae demonstrate substantial protein content ranging from 36-46% on a dry matter basis, though values vary considerably depending on rearing substrates (Almeida *et al*., 2020). Protein hydrolysates produced from BSF larvae through enzymatic hydrolysis contain lysine (8.0%), leucine (7.7%), and valine (7.2%) as predominant amino acids (Firmansyah & Abduh, 2019). Enzymatic hydrolysis using bromelain produces protein hydrolysates with molecular weights between 14-25 kDa and demonstrates significant antioxidant activity with 72.6% free radical inhibition capability (Firmansyah & Abduh, 2019). BSF larvae also possess a well-developed innate immune system producing antimicrobial peptides (AMPs) capable of inhibiting various microorganisms by targeting cell envelopes (Almeida *et al*., 2020).

Extraction Methods of *Hermetia illucens* Larvae

Mechanical pressing is a simple lipid extraction method. However, when it combined with freeze-drying, it often results in higher residual fat in the defatted meal, which may reduce protein concentration (Cantero-Bahillo *et al*., 2022). In contrast, aqueous enzymatic extraction offers a more balanced approach, achieving approximately 80% lipid recovery under mild processing conditions while preserving lipid quality (Wu *et al*., 2023). Solvent-based techniques, including maceration, decoction, microwave-, and ultrasound-assisted extraction using solvents such as water, acetone, and *n*-hexane, have also been explored, with ultrasound-assisted *n*-hexane extraction yielding the highest lipid recovery and strong antioxidant activity (Wu *et al*., 2023). Among advanced methods, supercritical CO_2 extraction stands out due to its low critical temperature (31.04 °C), which minimizes thermal degradation, enhances mass transfer, and enables efficient defatting, producing BSF powders with protein contents up to 64% and residual fat as low as 6% (Kim *et al*., 2021; Cruz *et al*., 2023). Additionally, this solvent-free technique generates clean extracts suitable for cosmetic and pharmaceutical applications, with extraction efficiency strongly influenced by sample pretreatment and operating conditions, particularly freeze-drying and pressure–temperature optimization (Cantero-Bahillo *et al*., 2022; Tan *et al*., 2021).

Enzymatic hydrolysis of defatted *Hermetia illucens* biomass has been extensively optimized, particularly using bromelain, where enzyme concentration (1–5%), pH (6–8), and hydrolysis time (3–24 h) significantly influence hydrolysate yield and quality. Under optimal conditions, hydrolysate yields of 10.70% (w/w) and degrees of hydrolysis ranging from 10–43% have been reported, with protein concentrations of 240–310 μg/mL (Firmansyah & Abduh, 2019). Higher yields (≈19.25%) can be achieved using mixed protease systems, such as alkaline protease and trypsin (1:1), under pH 7.0 at 54 °C for 4 h (Liu *et al*., 2024).

Bioactivities of Oil Extracts

Lipids are among the most valuable bioactive components derived from *Hermetia illucens* larvae, attracting increasing attention for their potential use in cosmetic formulations. The lipid fraction of BSF larvae is rich in medium- and long-chain fatty acids whose composition can be tailored through dietary manipulation, making it a versatile and sustainable source of functional ingredients. These lipids are known to play important roles in skin health, including barrier reinforcement, antimicrobial defense, oxidative stress protection, and modulation of inflammatory responses. Consequently, oil extracts from BSF larvae have emerged as promising candidates for multifunctional cosmetic applications.

1. **Antimicrobial activity**

   The antibacterial properties of *Hermetia illucens* larvae lipids are primarily attributed to their content of medium-chain and unsaturated fatty acids, notably lauric, oleic, and linoleic acids. These fatty acids exert antimicrobial effects by directly interacting with bacterial lipid membranes, leading to increased membrane permeability, leakage of intracellular constituents, and impairment of proton gradients and membrane-associated enzymatic activity. Lauric acid may also be metabolized into monolaurin, a compound with strong bactericidal activity, particularly against Gram-positive bacteria commonly implicated in skin disorders such as acne (Phongpradist *et al*., 2023).

   Previous findings indicate that several BSF lipid extracts effectively inhibit the growth of acne-associated Gram-positive bacteria, including *Cutibacterium acnes* and *Staphylococcus aureus*. This inhibitory activity is closely linked to bioactive fatty acids, especially lauric and oleic acids, which compromise bacterial cell membrane integrity and interfere with microbial metabolic processes (Santos Filipe *et al*., 2024).

2. **Anti-inflammatory activity**

   The anti-inflammatory action of BSF larvae-derived lipids is closely linked to the presence of bioactive fatty acids, with oleic acid being the predominant component. Oleic acid is recognized for its ability to modulate inflammatory pathways by inhibiting macrophage activation, decreasing inducible nitric oxide synthase (iNOS) expression, and lowering the release of pro-inflammatory mediators (Santos Filipe *et al*., 2024). It refers that an anti-inflammatory effect relevant for alleviating erythema and inflammation in acne-prone skin. Consequently, lipid extracts derived from *H. illucens* larvae demonstrate considerable promise as active ingredients in anti-acne cosmetic formulations due to their combined antimicrobial and anti-inflammatory properties (Santos Filipe *et al*., 2024).

3. Antioxidant and photoprotective activity

The antioxidant effects of *Hermetia illucens* larval oil are mediated through multiple concurrent mechanisms, including scavenging of free radicals, electron-donating activity, and suppression of lipid peroxidation. A variety of lipid constituents, such as unsaturated fatty acids, sterols, and potentially tocopherol fractions, contribute to the neutralization of reactive oxygen species (ROS) and interruption of oxidative chain reactions. In cellular models, BSF lipids have been demonstrated to lower intracellular ROS levels in UVB-exposed skin fibroblasts, thereby protecting cells against oxidative injury and delaying premature skin aging (Phongpradist *et al*., 2023). The photoprotective role of BSF lipids is mainly indirect and biological in nature, rather than functioning as conventional physical or chemical UV filters. Their protective effect is achieved by limiting UV-induced ROS generation, which in turn reduces oxidative stress, cellular damage, and the activation of inflammatory pathways following UV exposure.

4. Fatty acids and their potential in cosmetic applications

Lauric acid and other fatty acids present in the lipid fraction of *H. illucens* larvae can function as emulsifying and stabilising agents in dispersion systems and are widely utilised in soap and cosmetic manufacturing (Ushakova *et al*., 2016). The high lauric acid content of *H. illucens* oil further enhances its suitability for incorporation into skin cosmetic formulations compared with other natural oils. However, purification processes are recommended to eliminate undesirable phospholipids and free fatty acids, as well as to improve the oil's colour and odour characteristics (Almeida *et al*., 2020).

As discussed previously, fatty acids are widely utilized in cosmetic formulations; therefore, additional constituents of *Hermetia illucens* larval oil may also be employed, either as individual compounds or in the form of structured lipid complexes (Ushakova *et al*., 2016; Mank & Polonska, 2016). Oleic acid is known to stimulate lipid metabolism, enhance skin barrier repair, and promote moisture retention within the stratum corneum. Myristic acid is commonly incorporated into cosmetic products as a thickening and emulsion-stabilizing agent, while also contributing to skin barrier recovery and improving the penetration of active ingredients into the skin (Mank & Polonska, 2016). Palmitic acid and its derivatives function as emulsifiers and emollients in creams and lotions. Linoleic acid plays a crucial physiological role in preserving the skin's water permeability barrier, as it is an essential component of acylglycosyl ceramides that provide structural integrity to the stratum corneum. Insufficient levels of linoleic acid have been associated with the development of dermatitis in both adults and children (Almeida *et al*., 2020).

Bioactivities of Protein Hydrolysates and Peptides

Larvae of *Hermetia illucens* are recognized as a highly promising bioresource due to their high protein content, reaching approximately 40–50% of dry weight. Proteins are macromolecules composed of amino acids linked by peptide bonds and can be hydrolyzed into smaller fragments through chemical or enzymatic processes to produce protein hydrolysates. Among these approaches, enzymatic hydrolysis is widely applied because it allows better control over peptide size and minimizes excessive protein degradation (Firmansyah & Abduh, 2019; Abduh *et al*., 2023). BSF protein hydrolysates consist of a complex mixture of oligopeptides, short peptides, and free amino acids, some of which exhibit specific biological activities and are therefore classified as bioactive hydrolysates (Firmansyah & Abduh, 2019).

Previous studies have demonstrated that enzymatic hydrolysis of BSF larval proteins significantly enhances antioxidant activity by generating low molecular weight peptides with promising amino acid compositions (Firmansyah & Abduh, 2019). Furthermore, the degree of hydrolysis and enzymatic conditions strongly influence the functional and bioactive properties of the resulting hydrolysates, particularly their radical scavenging capacity (Abduh *et al*., 2023). These antioxidant properties are highly relevant for cosmetic applications, as oxidative stress is a major contributor to skin aging, inflammation, and barrier dysfunction. Owing to their natural origin, multifunctional bioactivity, and adjustable properties, BSF-derived protein hydrolysates represent a sustainable and innovative candidate for development as active ingredients in cosmetic and dermatological formulations (Firmansyah & Abduh, 2019; Abduh *et al*., 2023).

1. **Antioxidant activity**

   Protein hydrolysates derived from *Hermetia illucens* larvae have attracted increasing scientific attention due to their notable antioxidant properties and multifunctional bioactivity, positioning them as promising bioactive ingredients for cosmetic and dermatological applications. Enzymatic hydrolysis has been consistently reported as a critical process to enhance the release of low molecular weight peptides with strong radical scavenging and cytoprotective activities. Previous research by Firmansyah & Abduh (2019) demonstrated that controlled enzymatic hydrolysis of BSF larval proteins yielded hydrolysates exhibiting significant antioxidant capacity, as measured by DPPH and ABTS assays, indicating their effectiveness in neutralizing reactive oxygen species (ROS). These findings highlighted the role of peptide size and amino acid composition, particularly hydrophobic and aromatic residues in determining antioxidant activity.

Other studies elucidated the relationship between structure and function of BSF protein hydrolysates. Batish *et al*. (2020) reported that enzymatic hydrolysis not only improved antioxidant activity but also altered protein secondary structures, increasing surface hydrophobicity and exposure of functional amino acid residues. The enhanced antioxidant activity was correlated with increased solubility and emulsifying properties, which are particularly advantageous for cosmetic formulations that require stability and compatibility with both aqueous and lipid phases. These functional improvements point the dual technological and bioactive value of BSF-derived hydrolysates.

More recent investigations have extended antioxidant evaluation beyond chemical assays toward biological relevance. Riolo *et al*. (2023) demonstrated that BSF protein hydrolysates exerted cytoprotective effects against oxidative stress in cellular models, significantly reducing intracellular ROS levels and enhancing cell viability. This biological antioxidant activity is especially relevant to cosmetic applications aimed at skin protection, anti-aging, and barrier repair, where oxidative stress is a key contributor to inflammation, premature aging, and loss of skin integrity. The ability of BSF hydrolysates to modulate oxidative damage at the cellular level strengthens their potential as functional cosmetic bioactives rather than auxiliary antioxidants.

In addition, Abduh *et al*. (2023) confirmed that the degree of hydrolysis plays a pivotal role in maximizing antioxidant activity, with optimized enzymatic conditions producing hydrolysates rich in bioactive peptides capable of effective free radical scavenging. Their findings support the reproducibility and scalability of BSF hydrolysate production, an important consideration for industrial cosmetic applications.

These studies provide strong scientific evidence that antioxidant-rich BSF larval protein hydrolysates possess not only robust radical scavenging capacity but also favorable functional and cytoprotective properties. Given their natural origin, biodegradability, and multifunctional performance, BSF protein hydrolysates represent a sustainable and innovative alternative to conventional synthetic antioxidants in cosmetic formulations, particularly for anti-aging, anti-pollution, and skin-protective products (Firmansyah & Abduh, 2019; Batish *et al*., 2020; Riolo *et al*., 2023; Abduh *et al*., 2023).

2. Antimicrobial activity

Larvae of the black soldier fly (*Hermetia illucens*) represent a rich and highly diverse source of antimicrobial peptides (AMPs), reflecting their adaptation to microbe-dense environments such as decaying organic matter and manure. Bioinformatic and experimental studies have demonstrated that BSF larvae produce a wide spectrum of AMPs with potent antibacterial activity against several human pathogens, underscoring the robustness of their innate immune system (Moretta *et al*., 2020; Szczepanik & Świątkiewicz, 2024). AMPs are generally small peptides composed of 10–100 amino acids, characterized by a net positive charge and amphipathic structures that facilitate electrostatic interactions with negatively charged microbial membranes, ultimately leading to membrane disruption, intracellular targeting, or metabolic interference (Moretta *et al*., 2020). Owing to their exceptional biodiversity, insects and BSF in particular, are regarded as one of the most innovative reservoirs of novel AMPs with therapeutic potential.

Comprehensive transcriptomic analyses of BSF larvae and adults have led to the identification of at least 57 putatively active AMPs belonging primarily to defensins, cecropins, attacins, diptericins, and lysozymes (Moretta *et al*., 2020). Among these, defensins and cecropins constitute the most abundant and functionally relevant families. Insect defensins are small cysteine-rich peptides (approximately 38–45 amino acids) stabilized by three disulfide bridges and are predominantly active against Gram-positive bacteria, including *Staphylococcus aureus* and *Micrococcus luteus*, although some members also exhibit activity against Gram-negative bacteria and fungi (Van Moll *et al*., 2022; Fahmy *et al*., 2024). Cecropins, in contrast, are linear α-helical peptides lacking cysteine residues and are primarily bactericidal against Gram-negative bacteria, such as *Escherichia coli* and *Pseudomonas aeruginosa*, through membrane permeabilization and inhibition of nutrient uptake (Park & Yoe, 2017; Van Moll *et al*., 2022).

In vitro studies have validated the antimicrobial efficacy of several BSF-derived AMPs, particularly cecropins and defensins, against clinically relevant human pathogens, confirming the predictive value of bioinformatic screening approaches (Di Somma *et al*., 2022; Van Moll *et al*., 2022). However, despite the demonstrated activity of BSF AMPs against both Gram-positive and Gram-negative bacteria, no in vitro or in vivo studies to date have specifically evaluated their antibacterial activity against *Cutibacterium acnes*, a Gram-positive anaerobe and a key etiological agent of acne vulgaris. This represents a significant research gap, especially given that *C. acnes* expresses virulence factors such as lipases that contribute to inflammation and follicular dysbiosis.

Given the cationic nature, amphipathic structure, and proven efficacy of BSF defensins against Gram-positive bacteria, these peptides may possess strong inhibitory potential against *C. acnes*. Future research should therefore prioritize in silico molecular docking and molecular dynamics simulations to assess interactions between BSF-derived AMPs and essential *C. acnes* targets, including lipase and cell membrane components. Such computational analyses could guide peptide selection for subsequent in vitro validation and support the development of BSF-derived AMPs as novel anti-acne agents for dermatological and cosmetic applications (Moretta *et al.*, 2020; Szczepanik & Świątkiewicz, 2024).

Comparative Biological Activities: Lipid vs Protein Hydrolysates

Black soldier fly (BSF) larvae have emerged as a sustainable source of multifunctional cosmetic bioactives, primarily explored through lipid (oil) extracts and, to a much lesser extent, protein-derived hydrolysates. Current evidence strongly favors BSF oil extracts, which have been extensively characterized for dermocosmetic efficacy, while the cosmetic potential of BSF protein hydrolysates remains underinvestigated.

BSF oil extracts are enriched in medium- and long-chain fatty acids, such as lauric, oleic, linoleic, and palmitic acids, along with minor lipid-soluble antioxidants. These components confer broad biological activity relevant to skin aging and protection. In vitro studies have demonstrated that BSF oil effectively inhibits hyaluronidase, suppresses oxidative stress, reduces tyrosinase activity, and provides UVB protection, supporting its classification as a high-functional cosmetic bioactive (Phongpradist *et al*., 2023). These activities are mechanistically linked to fatty acid–mediated membrane stabilization, antioxidant capacity, and modulation of enzyme activity involved in extracellular matrix degradation and melanogenesis. Complementary findings further indicate that BSF lipid extracts enhance skin barrier function and oxidative resilience, reinforcing their applicability in anti-aging, whitening, and photoprotective formulations (Santos Filipe *et al*., 2024).

In contrast, BSF protein hydrolysates composed of low molecular weight peptides and free amino acids generated through enzymatic hydrolysis, have been primarily studied for nutritional and biomedical applications, with cosmetic-oriented research still limited. Nevertheless, these hydrolysates exhibit well-documented antioxidant activity through radical scavenging, metal chelation, and electron-donating mechanisms, largely attributed to hydrophobic and aromatic amino acid residues. Such properties are highly relevant to cosmetic science, given the central role of oxidative stress in skin aging, inflammation, and UV-induced damage. Moreover, bioactive peptides from non-insect sources are known to inhibit matrix-degrading enzymes and modulate skin-related cellular pathways, suggesting that BSF-derived peptides may possess analogous functionalities.

A critical distinction between the two BSF fractions lies in their mode of action. Lipid extracts primarily exert effects via lipid restoration, membrane interactions, and lipid-soluble antioxidant activity, whereas protein hydrolysates act through peptide–enzyme interactions, redox modulation, and potential signaling effects at the cellular level. This mechanistic divergence suggests a complementary, rather than competitive, relationship between BSF oil and protein hydrolysates in cosmetic formulations.

As an anti-acne, BSF oil extracts and BSF protein hydrolysates exhibit distinct yet potentially complementary activities against *Cutibacterium acnes*. BSF oil extracts, rich in lauric and unsaturated fatty acids, have been extensively studied and demonstrate indirect anti-acne potential through membrane-disruptive antibacterial effects, antioxidant activity, and inhibition of enzymes associated with skin degradation and inflammation. Although direct assays against *C. acnes* remain limited, their ability to reduce oxidative stress, inhibit hyaluronidase, and provide UVB protection supports their relevance for acne-prone skin (Phongpradist *et al*., 2023; Santos Filipe *et al*., 2024). In contrast, BSF protein hydrolysates composed of short bioactive peptides, remain largely unexplored for cosmetic anti-acne applications. Given that BSF-derived peptides exhibit strong antibacterial activity against Gram-positive pathogens via electrostatic membrane interactions, they may effectively target *C. acnes*, a Gram-positive anaerobe implicated in acne pathogenesis.

Despite the robust evidence supporting BSF oil as a multifunctional cosmetic ingredient, the lack of systematic studies evaluating BSF protein hydrolysates for hyaluronidase inhibition, melanogenesis regulation, and UVB protection represents a significant knowledge gap. Addressing this gap through targeted in vitro and in silico studies may reveal novel peptide-based cosmetic actives and broaden the functional scope of BSF-derived ingredients.

Molecular Mechanisms and Targets of BSF-Derived Antimicrobial Peptides and Lipids

Black Soldier Fly (*Hermetia illucens*) larvae produce cationic, amphiphilic antimicrobial peptides (AMPs) that preferentially target microbial membranes via electrostatic interactions with negatively charged components such as lipopolysaccharides in Gram-negative bacteria and teichoic acids in Gram-positive bacteria. Once bound, AMPs destabilize lipid bilayers through mechanisms including toroidal pore formation, barrel-stave insertion, carpet-like aggregation, and unstructured ring pores, ultimately resulting in cytoplasmic leakage and bacterial cell death (Li *et al*., 2017). Cecropins, a major AMP family in BSF, employ the carpet-like mechanism, assembling across the bacterial membrane to act like detergents, causing lipid bilayer collapse (Brady *et al*., 2019; Billah *et al*., 2024). Beyond membrane disruption, certain antimicrobial peptides (AMPs) can translocate into microbial cells and interact with intracellular targets such as DNA, RNA, and essential enzymes to impair processes like nucleic acid synthesis, protein production, and cell division, contributing to their antimicrobial efficacy through mechanisms that extend beyond simple pore formation in the membrane (Kim *et al*., 2025).

Structural parameters such as net positive charge, hydrophobicity, amphipathic helicity, and segmental distribution critically determine antimicrobial efficacy and selectivity, with optimal balance achieving maximal microbial inhibition while sparing host cells (Van Moll *et al*., 2022; Pimchan *et al*., 2024).

BSF lipid extracts provide complementary mechanistic benefits through bioactive fatty acids, particularly medium-chain saturated fatty acids (lauric acid) and polyunsaturated fatty acids (linoleic acid), which function as antimicrobial, anti-inflammatory, and antioxidant agents (Firmansyah & Abduh, 2019; Almeida *et al*., 2020). Lauric acid exhibits potent Gram-positive antibacterial activity, likely mediated by membrane perturbation and local pH modulation, and reduces bacterial loads in dermal infection models (Almeida *et al.*, 2020; Suryati *et al*., 2023). Linoleic acid contributes to enzymatic inhibition, including hyaluronidase suppression, thereby preserving extracellular matrix integrity and skin hydration (Phongpradist *et al*., 2023). BSF lipids also mitigate UVB-induced oxidative stress in fibroblasts and suppress melanogenesis by targeting tyrosinase activity, highlighting dual intracellular and extracellular mechanisms of action relevant for skin photoprotection and depigmentation (Phongpradist *et al.*, 2023; Lai-Foenander *et al.*, 2024).

As a whole, mechanistic insights reveal that the efficacy of BSF AMPs and lipids stems from a synergistic combination of membrane-targeting, intracellular inhibition, and enzyme modulation, with structure-activity relationships dictating bioactivity. Understanding these molecular targets is essential for optimizing extraction, formulation, and biotechnological enhancement of BSF-derived ingredients, enabling their translation into safe, multifunctional cosmetic and dermatological applications (Santos Filipe *et al.*, 2024).

Future Perspectives

Black soldier fly (BSF) larvae (*Hermetia illucens*) play a pivotal role in circular economy models by efficiently converting diverse organic waste streams into value-added biomass, reducing waste volumes by 50–80% while transforming approximately 20% into protein-, lipid-, and bioactive-rich materials (Wilson *et al.*, 2025). Larval growth performance and biochemical composition are strongly substrate-dependent, with animal-derived wastes enhancing biomass yield, while plant-based substrates promote the accumulation of polyphenols and other bioactive compounds (Camperio *et al.*, 2025). Additionally, feed-engineering strategies enable the enrichment of larval biomass with plant-derived polyphenols, further enhancing antioxidant capacity. BSF larvae valorisation supports the development of eco-friendly cosmetic actives while contributing to waste reduction, greenhouse gas mitigation, and sustainable beauty innovation aligned with green chemistry principles.

The cosmetic industry is experiencing a paradigm shift toward ingredients that address multiple skin concerns simultaneously, moving away from single-function actives toward comprehensive skincare solutions. Modern cosmetic formulations are expected to address several functional needs simultaneously, including enhanced active ingredient bioavailability, sustained hydration maintenance, and personalized compatibility with diverse skin phenotypes. Bioactive peptides extracted from various sources exhibit single or multifunctional cosmetic properties, including anti-aging, antioxidant, anti-inflammatory, and antimicrobial activities (Almeida *et al.*, 2020). Peptides offer high potency at low concentrations, good biocompatibility, and targeted mechanisms of action, making them ideal for anti-aging, hydration, and skin health applications.

Future development should focus on Synergistic component identification like screening *H. illucens* protein hydrolysates and lipid fractions to identify naturally co-occurring bioactive sequences with complementary mechanisms, developing standardized extraction protocols that preserve multiple bioactive functions rather than optimizing for single activities, and designing peptide combinations that synergistically activate cellular energy-associated pathways and repair mechanisms in skin cells (Franco *et al*., 2021). The integration of lipid and protein fractions from *H. illucens* represents a particularly promising avenue, as these components naturally complement each other's bioactivities and delivery characteristics. The future of *H. illucens*-derived ingredients in cosmeceuticals should be supported by rigorous clinical validation and mechanistic understanding. This approach bridges the gap between sustainable cosmetics and evidence-based dermatological products, positioning insect-derived bioactives as next-generation ingredients for skin health.

CONCLUSION

This review highlights *Hermetia illucens* larvae as a sustainable and valuable source of multifunctional cosmetic bioactives. Both BSF oil extracts and protein hydrolysates exhibit biological activities relevant to skin health. Oil extracts, rich in lauric, oleic, linoleic, and palmitic acids, demonstrate antimicrobial, antioxidant, anti-inflammatory, and photoprotective effects, supporting their use in anti-acne, anti-aging, and sun protection formulations through mechanisms such as bacterial membrane disruption, oxidative stress reduction, and skin barrier reinforcement.

BSF protein hydrolysates contain antioxidant peptides and antimicrobial peptides, including defensins and cecropins, which protect against oxidative damage and bacterial growth. However, compared to lipid extracts, cosmetic research on protein hydrolysates remains limited. Importantly, lipid and protein fractions act through distinct yet complementary mechanisms, suggesting that combined formulations may provide enhanced cosmetic efficacy by targeting multiple biological pathways.

From a sustainability perspective, BSF larvae efficiently convert organic waste into high-value cosmetic ingredients, supporting circular economy principles with a reduced environmental footprint. Advanced extraction technologies, such as supercritical CO_2 extraction and enzymatic hydrolysis, further enable the recovery of high-quality bioactives. Future studies should prioritize expanding cosmetic evaluations of protein hydrolysates, clinical validation, safety assessment, and the development of standardized, synergistic lipid–peptide formulations to facilitate commercial application.

REFERENCES

Abduh, M. Y., Prawitasari, D. A., Fitrian, U. A., & Firmansyah, M. (2023). Effects of enzymatic hydrolysis on the antioxidant activity of protein hydrolysate derived from the larvae of black soldier fly (*Hermetia illucens* L.). *Journal of Applied Biology & Biotechnology, 11*(2), 151–157. https://doi.org/10.7324/JABB.2023.110215

Almeida, C., Rijo, P., & Rosado, C. (2020). Bioactive compounds from *Hermetia illucens* larvae as natural ingredients for cosmetic application. *Biomolecules, 10*(7), 976. https://doi.org/10.3390/biom10070976

Batish, I., Brits, D., Valencia, P., Miyai, C., Rafeeq, S., Xu, Y., et al. (2020). Effects of enzymatic hydrolysis on the functional properties, antioxidant activity and protein structure of black soldier fly (*Hermetia illucens*) protein. *Insects, 11*(12), 876. https://doi.org/10.3390/insects11120876

Billah, M. M., Ahmed, M., Islam, M. Z., & Yamazaki, M. (2024). Processes and mechanisms underlying burst of giant unilamellar vesicles induced by antimicrobial peptides and compounds. *Biochimica et Biophysica Acta (BBA) – Biomembranes, 1866*(5), 184330. https://doi.org/10.1016/j.bbamem.2024.184330

Brady, D., Grapputo, A., Romoli, O., & Sandrelli, F. (2019). Insect cecropins: Antimicrobial peptides with potential therapeutic applications. *International Journal of Molecular Sciences, 20*(23), 5862. https://doi.org/10.3390/ijms20235862

Camperio, J., Suarez, J. A., Simonton, J., Paresky, E., Parodi, J., & Benetti, D. D. (2025). Valorizing organic waste through black soldier fly larvae (*Hermetia illucens*): A sustainable solution for aquafeeds with key nutrients and natural bioactive polyphenols. *Sustainability, 17*(5), 1788. https://doi.org/10.3390/su17051788

Cantero-Bahillo, E., Navarro del Hierro, J., Hernández, M. D., & Fernández-Felipe, M. T. (2022). Supercritical CO_2 for defatting and production of bioactive extracts from black soldier fly (*Hermetia illucens*) larvae. *Journal of Insects as Food and Feed, 8*(12), 1441–1454. https://doi.org/10.3920/JIFF2021.0210

Cruz, V., Ferreira, N., Cornelio-Santiago, H., Santos, G. M. T., & Oliveira, A. (2023). Oil extraction from black soldier fly (*Hermetia illucens* L.) larvae meal by dynamic and intermittent processes of supercritical CO_2. *The Journal of Supercritical Fluids, 194*, 105861. https://doi.org/10.1016/j.supflu.2023.105861

Di Somma, A., Moretta, A., Cané, C., Scieuzo, C., Salvia, R., Falabella, P., et al. (2022). Structural and functional characterization of a novel recombinant antimicrobial peptide from *Hermetia illucens*. *Current Issues in Molecular Biology, 44*(1), 1–13. https://doi.org/10.3390/cimb44010001

Fahmy, L., Generalovic, T., Ali, Y. M., Seilly, D., Sivanesan, K., Kalmar, L., et al. (2024). A novel family of defensin-like peptides from *Hermetia illucens* with antibacterial properties. *BMC Microbiology, 24*(1), 167. https://doi.org/10.1186/s12866-024-03325-1

Firmansyah, M., & Abduh, M. Y. (2019). Production of protein hydrolysate containing antioxidant activity from *Hermetia illucens*. *Heliyon, 5*(6), e02005. https://doi.org/10.1016/j.heliyon.2019.e02005

Franco, A., Salvia, R., Scieuzo, C., Schmitt, E., Russo, A., & Falabella, P. (2021). Lipids from insects in cosmetics and for personal care products. *Insects, 13*(1), 41. https://doi.org/10.3390/insects13010041

Gatlin, D. M., 3rd, Carvalho, P. L. P. F., Flint, C., Miranda, C., & Tomberlin, J. K. (2024). Evaluation of lauric acid enhancement of black soldier fly larvae from coconut. *Journal of economic entomology*, *117*(4), 1235–1241. https://doi.org/10.1093/jee/toae093

Gold, M., Tomberlin, J. K., Diener, S., Zurbrügg, C., & Mathys, A. (2018). Decomposition of biowaste macronutrients, microbes, and chemicals in black soldier fly larval treatment: A review. *Waste Management*, *82*, 302–318. https://doi.org/10.1016/j.wasman.2018.10.022

Kim, C. H., Ryu, J., Lee, J., Ko, K., Lee, J. Y., Park, K. Y., & Chung, H. (2021). Use of black soldier fly larvae for food waste treatment and energy production in Asian countries: A review. *Processes, 9*(1), 161. https://doi.org/10.3390/pr9010161

Kim, S. H., Min, Y. H., & Park, M. C. (2025). Antimicrobial Peptides: Current Status, Mechanisms of Action, and Strategies to Overcome Therapeutic Limitations. *Microorganisms*, *13*(11), 2574. https://doi.org/10.3390/microorganisms13112574

Lai-Foenander, A. S., Kuppusamy, G., Manogoran, J., Xu, T., Chen, Y., Tang, S. Y., et al. (2024). Black soldier fly (*Hermetia illucens* L.): A potential small mighty giant in cosmeceuticals. *Health Science Reports, 7*(6), e2120. https://doi.org/10.1002/hsr2.2120

Li, J., Koh, J. J., Liu, S., Lakshminarayanan, R., Verma, C. S., & Beuerman, R. W. (2017). Membrane active antimicrobial peptides: translating mechanistic insights to design. *Frontiers in Neuroscience, 11*, 73. https://doi.org/10.3389/fnins.2017.00073

Liu, G., Tiang, M. F., Ma, S., Wei, Z., Liang, X., Sajab, M. S., et al. (2024). An alternative peptone preparation using *Hermetia illucens* hydrolysis: process optimization and performance evaluation. *PeerJ, 12*, e16995. https://doi.org/10.7717/peerj.16995

Mank, V., & Polonska, T. (2016). Use of natural oils as bioactive ingredients of cosmetic products*. Ukrainian Food Journal, 5*(2), 281–289. https://doi.org/10.24263/2304-974x-2016-5-2-7

Moretta, A., Salvia, R., Scieuzo, C., Di Somma, A., Vogel, H., Pucci, P., et al. (2020). A bioinformatic study of antimicrobial peptides identified in the black soldier fly (BSF) *Hermetia illucens* (Diptera: Stratiomyidae). *Scientific Reports, 10*, 16875. https://doi.org/10.1038/s41598-020-74017-9

Park, S. I., & Yoe, S. M. (2017). A novel cecropin-like peptide from black soldier fly, *Hermetia illucens*: isolation, structural and functional characterization. *Entomological Research, 47*(2), 115–124. https://doi.org/10.1111/1748-5967.12226

Pimchan, T., Hamzeh, A., Siringan, P., Thumanu, K., Hanboonsong, Y., & Yongsawatdigul, J. (2024). Antibacterial peptides from black soldier fly larvae: mode of action and characterization. *Scientific Reports, 14*(1), 26469. https://doi.org/10.1038/s41598-024-73766-1

Phongpradist, R., Semmarath, W., Kiattisin, K., Jiaranaikulwanitch, J., Chaiyana, W., Chaichit, S., Phimolsiripol, Y., Dejkriengkraikul, P., & Ampasavate, C. (2023). The *in vitro* effects of black soldier fly larvae (*Hermitia illucens*) oil as a high-functional active ingredient for inhibiting hyaluronidase, anti-oxidation benefits, whitening, and UVB protection. *Frontiers in pharmacology*, *14*, 1243961. https://doi.org/10.3389/fphar.2023.1243961

Riolo, K., Rotondo, A., La Torre, G. L., Marino, Y., Franco, G. A., Crupi, R., Fusco, R., Di Paola, R., Oliva, S., De Marco, G., Savastano, D., Cuzzocrea, S., Gugliandolo, E., & Giannetto, A. (2023). Cytoprotective and Antioxidant Effects of Hydrolysates from Black Soldier Fly (*Hermetia illucens*). *Antioxidants (Basel, Switzerland)*, *12*(2), 519. https://doi.org/10.3390/antiox12020519

Santos Filipe, M., Cardoso, R. V. C., Ayuso, M., Murta, D., Díaz-Lanza, A. M., Rosado, C., et al. (2024). Exploring the potential of *Hermetia illucens* larvae extracts: A promising approach for dermocosmetic formulations. *Heliyon, 10*, e37395. https://doi.org/10.1016/j.heliyon.2024.e37395

Suryati, T., Julaeha, E., Farabi, K., Ambarsari, H., & Hidayat, A. T. (2023). Lauric acid from the black soldier fly (*Hermetia illucens*) and its potential applications. *Sustainability, 15*(13), 10383. https://doi.org/10.3390/su151310383

Szczepanik, K., & Świątkiewicz, M. (2024). *Hermetia illucens* as a source of antimicrobial peptides – a review of in vitro and in vivo studies. *Annals of Animal Science, 24*(1), 77–88. https://doi.org/10.2478/aoas-2023-0071

Tan, Y., Chin, Y., & Chen, W. (2021). Comparison of sustainable lipid and protein removal methods for the isolation of insect chitin from black soldier fly exoskeleton. *ACS Food Science & Technology, 1*(1), 77–86. https://doi.org/10.1021/acsfoodscitech.0c00104

Ushakova, N. A., Brodskii, E. S., Kovalenko, A. A., Bastrakov, A. I., Kozlova, A. A., & Pavlov, D. S. (2016). Characteristics of lipid fractions of larvae of the black soldier fly *Hermetia illucens*. *Doklady. Biochemistry and biophysics*, *468*(1), 209–212. https://doi.org/10.1134/S1607672916030145

Van Moll, L., De Smet, J., Paas, A., Tegtmeier, D., Vilcinskas, A., Cos, P., et al. (2022). In vitro evaluation of antimicrobial peptides from the black soldier fly (*Hermetia illucens*) against a Selection of Human Pathogens. *Microbiology Spectrum, 10*, e01664-21. https://doi.org/10.1128/spectrum.01664-21

Wilson, D. D., Ray, R. L., & Lohakare, J. (2025). Black soldier fly (*Hermetia illucens*) applications in circular economy and agricultural sustainability: A review. *Discover Sustainability, 6*, 1347. https://doi.org/10.1007/s43621-025-02250-1

Wu, L., Li, Z., Li, J., Fang, H., Qiu, X., Fu, P., & Zhu, T. (2023). Lipid extraction of black soldier fly larva using aqueous enzymatic and soxhlet method. *E3S Web of Conferences, 406*, 03013. https://doi.org/10.1051/e3sconf/202340603013