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A REVIEW OF SUSTAINABLE SOLUTION USING BLACK SOLDIER FLY LARVAE AND THEIR ROLE IN CONVERTING ORGANIC WASTE INTO BIO-BASED RESOURCES

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ABSTRACT

The escalating challenges of managing organic waste and the pressing need for sustainable alternatives in valuable products have fuelled interest in the potential of black soldier fly (BSF) larvae as an innovative and impactful solution. This review article comprehensively examines the multifaceted role of BSF in converting organic waste into valuable resources, particularly focusing on feeds, chitin, frass and biodiesel production. The introduction elucidates the significance of sustainable waste management and highlights the important role of BSF in this context. It highlights the importance of sustainable resource production methods and introduces BSF as a promising candidate. The article delves into the intricacies of organic waste management and the environmental ramifications of inadequate disposal, emphasising the urgent necessity for efficient waste conversion methodologies. The biological aspects of BSFL are expounded upon in the context of their life cycle, developmental stages, and nutritional requisites. An in-depth exploration of the conversion process reveals the feeding habits and substrate preferences of BSF, and the mechanisms underlying waste digestion and nutrient extraction. The bioconversion efficiency and waste reduction potential of BSF are critically evaluated, setting the stage for subsequent discussions on valorisation. The review emphasizes the diverse valorisation pathways of BSF, including their role as a nutrient-rich animal feed source. The environmental and economic benefits of BSF-based waste conversion are thoroughly examined, including reductions in organic waste volume and greenhouse gas emissions. A comparative analysis with conventional resource production methods is also presented. The article addresses challenges and limitations encompassing regulatory, ethical, and technological dimensions. Case studies and applications illustrate the successful integration of BSF in organic waste management and the production of valuable resources, demonstrating the feasibility and scalability of this approach, particularly in Malaysia.

Keywords: Biodiesel; feed; frass; chitin; chitosan; greenhouse gas

ABSTRAK

Cabaran yang semakin meningkat dalam pengurusan sisa organik serta keperluan mendesak terhadap alternatif lestari bagi penghasilan produk bernilai telah mendorong minat terhadap potensi larva lalat askar hitam (BSF) sebagai satu penyelesaian yang inovatif dan berimpak tinggi. Artikel ulasan ini meneliti secara komprehensif peranan pelbagai aspek larva BSF dalam menukar sisa organik kepada sumber bernilai, dengan tumpuan khusus pada penghasilan makanan ternakan, kitin, frass, dan biodiesel. Bahagian pengenalan menerangkan kepentingan pengurusan sisa secara lestari serta menekankan peranan signifikan larva BSF dalam konteks ini. Ia turut mengetengahkan kepentingan kaedah penghasilan sumber yang mampan dan memperkenalkan BSF sebagai calon yang berpotensi. Artikel ini mengupas secara mendalam aspek pengurusan sisa organik dan implikasi alam sekitar akibat pelupusan yang tidak efisien, sekali gus menekankan keperluan mendesak bagi metodologi penukaran sisa yang berkesan. Aspek biologi BSF dihuraikan dalam konteks kitaran hidup, peringkat perkembangan, dan keperluan nutrisi. Kajian mendalam mengenai proses penukaran sisa mendedahkan tabiat pemakanan dan keutamaan substrat BSF serta mekanisme pencernaan sisa dan pengekstrakan nutrien. Kecekapan biopenukaran dan potensi pengurangan sisa oleh BSF dinilai secara kritikal, yang seterusnya membentuk asas bagi perbincangan mengenai pemanfaatan sumber. Ulasan ini menekankan pelbagai laluan pemanfaatan BSF, termasuk peranannya sebagai sumber makanan haiwan yang kaya nutrien. Manfaat alam sekitar dan ekonomi dalam penukaran sisa berasaskan BSF dinilai secara menyeluruh, termasuk pengurangan jumlah sisa organik dan pelepasan gas rumah hijau. Analisis perbandingan dengan kaedah penghasilan sumber konvensional turut dibentangkan. Artikel ini turut membincangkan cabaran serta batasan yang merangkumi aspek peraturan, etika, dan teknologi. Kajian kes dan aplikasi menunjukkan kejayaan integrasi BSF dalam pengurusan sisa organik serta penghasilan sumber bernilai, sekali gus membuktikan kebolehlaksanaan dan potensi penskalaan pendekatan ini khususnya di Malaysia.

Kata kunci: Biodiesel; makanan ternakan; frass; kitin; kitosan; gas rumah hijau

INTRODUCTION

Meeting an ever-increasing worldwide population, projected from 7.3 billion in 2015 to 9.7 billion in 2050, which causes a high growth in the demand for animal feed, diet and the management of waste, especially organic waste, is one of the major issues in undeveloped and developing countries (Khan et al. 2025). Additionally, organic waste management is challenging due to its rapid biodegradability and immense nature. According to a report, approximately 1.3 tons of waste are produced daily and are expected to reach 3.40 billion by the year 2050 (Kaza et al. 2018). These applications constitute a danger to the environment and most importantly to community health due to greenhouse gas emissions and the discharge of toxic pollutants into soil and water (Khan et al. 2025). Furthermore, the poor hygiene factors at landfills endorse the growth of rodents, and vermin vectors that spread diseases such as malaria, and Asiatic Indian cholera throughout the public.

Therefore, there is an urgent need to develop more effective knowledge to report the issues related to waste generation. The decomposition of organic waste by using black soldier fly (BSF), *Hermetia illucens* is one of the safest, eco-friendly ways due to its multiple benefits, such as low cost and a short production time. Over the past few years, the BSF industry has been growing very fast in the utilization of organic waste conversion (Derrien & Boccuni 2018). Kim et al. (2021) stated that treatment of organic waste with BSF is biologically safe and can reduce many ecological issues such as the emission of greenhouse gases and the generation of harmful substances associated with current disposal methods such as landfills and burning, and is a cost-effective method that is gaining popularity around the world. Furthermore, BSF-based bioconversion is reported to be more economically viable (Noor Idzam et al. 2025) faster in reducing a significant quantity of waste by up to 80% in two weeks compared to a 10% reduction in eight weeks with vermicomposting and more sustainable concerning greenhouse gas and emissions of ammonia.

Black soldier fly larvae can utilize various organic resources, including food, agricultural, and animal waste, to produce diverse animal feeds (Surendra et al. 2020), and used as feed as an alternative to conventional feed (Khan et al. 2025). They serve as a protein source for domestic animals, poultry, pigs, and aquaculture species (Barragan-Fonseca et al. 2017). Recent studies conducted in Southeast Asia have emphasized the productivity of BSF larvae in bio-converting fruit and agricultural wastes, mainly banana peels, into valuable biomass (Gunggot & Lardizabal 2024). In addition, a recent systematic review on the application of palm kernel by-products in BSF bioconversion further highlights the importance of locally available agro-industrial residues, showing that palm-based wastes such as palm kernel meal and palm kernel expeller can serve as effective substrates for larval growth and nutrient recovery (Noor Idzam et al. 2025).

Moreover, the larvae and pupae of the BSF have been studied as a potential biofuel source (Surendra et al. 2016) and its by-product frass is used as fertilizer. Black soldier fly frass is considered to be a major output from these making systems (Schmitt & de Vries 2020) and with the upscaling production from BSF, the importance of frass is becoming more economically and environmentally significant. In addition, the pupae or larvae also present some of the bio-active compounds, fatty acids, chitin and antimicrobial peptides, which can add value to animal feeds. BSF is one of the sustainable and suitable technologies that can reduce treated sewage sludge (biosolids) by up to 40% in a short time and can produce high-value BSF larvae biomass with a low level of contaminants, such as heavy metals. BSF larvae have been shown to significantly reduce swine manure while producing valuable feed biomass and nutrient-rich residue (Newton et al. 2005). Therefore, BSF larvae can be regarded as potential decomposers in the natural environment, contributing to organic waste reduction (Hasan 2022). Given these diverse applications and ecological benefits, this review aims to comprehensively evaluate the valuable potential of the BSF, emphasizing its growth factors, nutritional requirements, animal feed applications, contributions to sustainable agriculture, and industrial uses in biodiesel and chitin-chitosan production.

Overview of Black Soldier Flies (*Hermetia illucens*)

Black soldier fly is a fascinating and ecologically important insect belonging to the family Stratiomyidae. It is native to North America but has nowadays spread to various regions globally due to human activity. The adult is relatively large, about 15-20 mm in length, with a distinct appearance characterized by its black colouration and smoky wings. Unlike other fly species, BSF are not known for transmitting diseases to humans, making them relatively safe and beneficial insects (Kim et al. 2021). The life cycle of the black soldier fly consists of egg, larva, pupa, and adult. Female black soldier flies lay between 500-1000 eggs near rotting organic matter, such as compost or food waste.

The most notable and economically significant stage is the larval stage. The BSF larvae undergo several instars (growth stages) during their larval phase, which typically lasts for about 14-21 days. The larvae are voracious eaters and are highly efficient at converting organic matter into biomass. They have a distinctive appearance, pale white with a tapered, and tough exoskeleton, and small black heads with mouthparts. BSF larvae are valuable decomposers and are often used in waste management and composting due to their capability to break down organic waste materials. After the larval stage, the BSF enter the pupal stage. During this stage, the larvae transform into pupae, where they undergo metamorphosis inside protective pupal cases. This transformation usually takes around 5-10 days and the adult BSF emerges from the pupal cases. Unlike some other fly species, adult BSF do not feed, and their primary purpose is to reproduce. They have a short lifespan, typically living for about 5-8 days (Hasan 2022).

Nutritional Requirements and Growth Factors

Black soldier fly larvae are renowned for their impressive capability to convert a wide range of organic materials into valuable biomass. They are highly efficient at recycling organic waste, making them an attractive option for sustainable waste management practices. BSF larvae have been studied for their potential in various applications, including animal feed production, bioconversion of organic waste, and even as a source of protein and fat for human consumption (Kim et al. 2021). The growth of BSF is influenced by several key factors, which are summarized in Table 1.

Table 1. Factors affecting BSF growth and development

Factors	Descriptions	References
Feeding substrate	The types of substrates used to rear the BSF affect the growth of the larvae. Restaurant waste produces the greatest larval length and weight. Fish waste produces the shortest developmental time and greatest yields regarding weight (biomass), length, and nutritional content. Fruit waste produces the lowest weight and length in the fly larvae/pre-pupae (immature stage), pre-pupal protein values were similar to commercial food.	Pérez-Pacheco et al. 2022
	BSFL thrive on a diverse variety of organic materials, such as kitchen scraps, food waste, agricultural residues, and manure.	Kim et al. 2021
The moisture content of the substrate	60 % to 80 % 50 % to 70 % 40 % to 70 %	Pérez-Pacheco et al. 2022
Temperature	25°C to 30°C (77-86°F) 26°C to 40°C	Pérez-Pacheco et al. 2022
pH level	pH 4.5 to pH 8	Kim et al. 2021

	Larval activity increases pH over time with final values around 8.9-9.4, regardless of the starting pH.	
Light exposure	BSF grows best in the wavelength range between 450 and 700 nm.	Zhang et al. 2010
Larval density	Lower density resulted in higher crude protein while higher density increased crude fat. Density also influences the concentrations of S, Mg, K, P, Fe, Zn, Cu, Al, B, Co and affected free amino acids (PPS, ALA, CIT, ANS).	Yakti et al. 2022
Feeding rate	As the feeding rate increases, the development time from larvae to pre-pupae decreases. The longest development time (20 days) was observed at the lowest feeding rate (0.25 g), while the shortest time (11 days) occurred at the highest feeding rate (2.00 g).	Yuan & Hasan 2022
Ventilation	Adequate airflow is crucial for preventing moisture buildup and ensuring optimal growth. Proper ventilation helps maintain the desired conditions for BSF development.	Kim et al. 2021

Valuable Resources from the Bioconversion of BSF

Black soldier fly larvae have emerged as a sustainable solution for converting organic waste into valuable products. These larvae efficiently process various organic materials, including food scraps and agricultural residues, into high-quality protein and oil, which serve as alternative ingredients in livestock and aquaculture feeds (Astuti & Wiryawan 2022). Aminuddin et al. (2023) stated that BSF larvae reared on kitchen and mixed organic wastes in Malaysia achieved lipid contents between 38-42%, while at the same time producing a substantial amount of protein and chitin, thereby demonstrating their efficiency in organic waste bioconversion. Additionally, the residual frass from BSF can be utilized as an organic fertilizer, enhancing soil health and reducing reliance on chemical fertilizers (Schmitt & de Vries 2020). This innovative approach not only addresses waste management challenges but also contributes to the development of a circular economy by transforming waste into other valuable resources, as summarized in Table 2.

Table 2. Products derived from BSF bioconversion of waste into valuable resources

Products	**Descriptions**	**References**
Protein meal	An alternative nutrient source for poultry and swine feed because they contain nearly 100% of the edible portion of protein.	Lu et al. 2022
Lipids	BSF has high lipid content ranging from 35% to 40%, hence it is a potential raw material for biodiesel production.	Wang et al. 2017

Chitin	Chitin extracted from BSF has numerous benefits in agriculture, medicine, water treatment, the food industry, cosmetics and packaging.	Chavez & Uchanski 2021 Baharlouei & Rahman 2022 Tao et al. 2020 Zhang et al. 2023 Morganti et al. 2006
Frass	Frass is a byproduct derived from BSF larvae that feed on organic wastes and can be used as fertilizer as an alternative approach that can be integrated with conventional fertilizers to optimize the cropping system.	Schmitt & de Vries 2020

Environmental Impact on Sustainable Agriculture

The use of chemical fertilizers has many negative effects, such as the reduction of soil organic matter, which leads to poor soil aggregation and degradation of soil structure. This condition results in nutrient loss through leaching, fixation, and gas emission, reducing fertilizer efficacy. In addition, excessive or prolonged application of chemical fertilizers decreases soil fertility by disrupting ionic balance, stimulating acidification, inducing salinity, and suppressing beneficial soil microbes (Nogalska et al. 2022).

To achieve a sustainable agricultural system, it is necessary to adopt organic fertilizers or organic farming practices that create an eco-friendly environment. In recent years, black soldier fly (BSF) frass has emerged as one of the most promising organic fertilizers. This by-product transforms organic waste into nutrient-rich biomass, serving as an excellent organic fertilizer. Frass, a term referring to the excreta and remains of insects such as food residue, exoskeleton sheds, and dead insects are valuable by-product from commercially produced insect larvae, including BSF (Schmitt & de Vries 2020).

Poultry Feed

Black soldier fly larvae offer a promising alternative protein source for chicken nutrition, enhancing production efficiency, health, and welfare due to their high protein and fat content. Their inclusion improves meat and egg quality by optimizing the lipid profile and increasing protein levels, making them a potential substitute for fish meal and soybeans (Zamri et al. 2023). Broilers nourished on partially replaced soybean meal substitutes (10-20%) showed comparable productivity, feed efficiency, mortality, and carcass characteristics to those fed commercial diets (Zhang et al. 2014b). These findings highlight BSF larvae as a viable ingredient in poultry feed formulations.

Compared to vegetable oils, BSF-derived oil is generally more palatable to fish. When fish waste is included in the larval diet, the resulting pre-pupae become enriched with omega-3 fatty acids. These findings suggest that incorporating BSF, either fully or partially, into poultry diets, combined with improved processing methods, can significantly enhance feed intake and overall performance (Abd El-Hack et al. 2020). BSF larvae also exhibit high levels of essential amino acids, offering a more favourable profile than soybean meal and conventional plant protein sources (Abd El-Hack et al. 2020).

The amino acid composition of BSF meal varies depending on rearing conditions, substrate, and developmental stage; however, it remains a widely accepted alternative to soybean meal in chicken diets (Abd El-Hack et al. 2020). Incorporating BSF meal into poultry diets has been shown to enhance weight gain, nutrient absorption, and overall health in both broilers and laying hens. The optimal inclusion level depends on the nutritional requirements and production objectives of each group. Overall, BSF serves as a nutrient-rich and functional feed ingredient suitable for sustainable poultry production.

Aquaculture Feed

The BSF makes a significant contribution to fish feed development among insect species. Nutritionally, BSF stores sufficient quantities of protein (30% to >50%) and lipid (20 to > 40%) (Diola et al. 2024). This variation is influenced by factors such as diet, farming conditions, life stages, and processing techniques. Adjusting these parameters allows for the optimization of lipid quantity and quality to achieve the desired nutritional profile for aquaculture feed applications. Research findings indicate that the fatty acid composition of BSF is primarily determined by the type and composition of the rearing substrates, while the vital amino acid makeup is comparable with that of fish (Müller et al. 2017).

A study by Saputra and Lee (2023) on the composition of commercial full-fat and defatted BSF larvae meal revealed that Malaysian BSF meal, in both forms, contains higher crude protein levels than fishmeal. Protein substitution in diets for fish has been studied using BSF prepupae and larvae across various species, including turbot (*Psetta maxima*) (Kroeckel et al. 2012), yellow catfish (*Tachysurus fulvidraco*) (Zhang et al. 2014a), channel catfish (*Ictalurus punctatus*) (Zhang et al. 2014a, 2014b). These studies revealed that low incorporation levels of BSF achieved growth results comparable to fish fed conventional feed, which might be attributed to higher larval protein levels (Zhang et al. 2014a). BSF-based diets have also proven effective for *Channa marulius*, yielding substantial growth and persistence rates comparable to chicken liver (Khubaib et al. 2024). However, higher levels of BSF inclusion (>33%) in fish diets may negatively influence fish growth, feed palatability, and protein digestibility (Kroeckel et al. 2012). The type of substrate used for raising BSF and the processing methods applied can further affect their acceptance by fish. Zarantoniello et al. (2019) evaluated BSF meal as a fishmeal substitute in zebrafish (*Danio rerio*) and found stable growth performance up to 25% inclusion. These findings indicate that the BSF meal serves as a viable alternative protein source in aquafeed. When used at appropriate inclusion levels, it supports optimal growth, feed efficiency, and general performance in a range of fish species, reinforcing its potential as a sustainable and high-value ingredient in aquaculture.

Feed for Other Animal Species

Complete BSF pupae and larvae were given to animals such as the mountain chicken frogs (*Leptodactylus fallax*) (Dierenfeld & King 2009). Larvae of BSF were fed to juvenile alligators entirely in place of conventional feeds, and the results were lower consumption and development rate than with conventional diets. Mountain chicken frogs fed with BSF exhibited low nutrient digestibility. Species that consume their feed whole, such as these frogs, seem to gain fewer nutritional benefits from unprocessed BSF. For example, the calcium absorption rate from whole BSF larvae was only 44%, compared to 88% when the larvae were ground before feeding. On the other hand, BSF have been effectively used in confined feeding and breeding programs for several lizard and amphibian species, mostly as a source of minerals (Dierenfeld & King 2009).

Biodiesel

The growing worldwide demand for biofuels and the need for sustainable waste management solutions have led to increased interest in exploring alternative sources of feedstock for biodiesel production (Surendra et al. 2016). Larvae of BSF have gained attention as a potential feedstock due to their rapid growth, efficient conversion of organic waste, and high lipid content. Lipids are the main component used for biodiesel production. BSF larvae have been found to accumulate substantial amounts of lipids, particularly during their prepupal stage. The lipid content can range from 30% to 50% of their dry weight, making them a potentially valuable source of feedstock for biodiesel production (Surendra et al. 2016).

Several studies have demonstrated the potential of BSF for biodiesel generation under various rearing conditions. Zheng et al. (2012) reared 1,000 BSF on 1 kg of solid organic waste, yielding 24 grams of biodiesel from the extracted fat. Additionally, the waste was reduced by nearly 62% within seven days. When 2,000 BSF were reared on a food waste mixture of rice straw and kitchen waste, biodiesel production increased to 44 grams within 10 days. In a similar study, 500 BSF reared on fermented corncobs produced only 3.2 grams of biodiesel within eight days, suggesting a lower nutritive value of this substrate. These findings indicate that biodiesel production is influenced by the fat content of the feeding substrate, with higher-fat substrates leading to greater yields. However, the extraction technique greatly influences biodiesel yield, as mechanical extraction tends to produce lower output, while solvent-based extraction achieves higher yields but demands a greater volume of solvents (Wang et al. 2017). In contrast to conventional diesel, biodiesel exhibits several advantageous properties, including high oxidative stability, low viscosity, a high cetane number, a high flash point, and low density. These attributes make it a suitable alternative fuel that can operate efficiently without significant engine or fuel system modifications.

Reports also indicate that BSF-derived biodiesel tends to have higher pour and cloud points than both conventional diesel and other biodiesel types. These properties affect cold flow performance, especially in colder climates. To address this, BSF biodiesel may require heating or blending with other fuels to lower its pour and cloud points, ensuring smoother operation under low temperatures (Hoc et al. 2019). Further research is therefore needed to identify effective additives and processing techniques to improve its cold flow and oxidation characteristics.

Integrating BSF into biodiesel production represents a step toward a more sustainable and eco-friendly biofuel industry. Despite its promise, challenges remain in optimizing larval growth conditions, scaling up mass production, and improving lipid extraction efficiency. Additionally, safety and regulatory frameworks must be developed to ensure consistent quality and compliance with energy standards. Globally, countries are investing in BSF biofuel research and production. South Korea has allocated over $100 million to advance BSF-based fuel initiatives within the next five years, while the Netherlands is supporting large-scale pilot plants and vehicle performance trials. Similarly, India, China, and the United States are exploring BSF-derived biofuels as sustainable energy alternatives to reduce pollution and dependence on fossil fuels (Khan et al. 2021).

Chitin and Chitosan

Chitin is a naturally occurring polymer that can be extracted from various organisms, primarily insects (Asad et al. 2024), including crustaceans and fungi, although its detailed study remains limited due to restricted availability. The medical and nutritional food research institutes in Europe and the United States have recognized chitin as the sixth essential factor for human health, following sugar, protein, fat, vitamins, and minerals (Elieh-Ali-Komi & Hamblin 2016). Mohd Hayati et al. (2022) stated that chitin can be obtained from several developmental stages of the BSF, including larvae, prepupae, and pupae. The extraction yield differs across these stages, with prepupae showing the lowest yield (24.4%) and pupae the highest (35.6%). This demonstrates the potential of BSF as a promising alternative source of chitin with distinct biochemical characteristics. Applications of chitin generated from BSF include biodegradable packaging, water filtration, tissue engineering, medicine delivery, and biofuel generation, as summarised in Table 3. Chitin can also be extracted via microbial fermentation using *Bacillus lichenformis* A6, yielding approximately 12.4% α-chitin, with total chitin and chitosan production reaching 52.8% and 55.4%, respectively. The biological extraction method is considered safer and more sustainable than chemical methods, as it reduces energy consumption, toxicity, and waste generation. Therefore, black soldier fly-derived chitin and chitosan present an environmentally responsible, economically viable, and sustainable alternative for high-quality industrial applications

Table 3. The application of chitin and chitosan in various fields

Applications	**Descriptions**	**References**
Agriculture	Function as a biopesticide by degrading chitin to low molecular weight, which disrupts the insect's exoskeleton and gut lining, eventually leading to death or less survival.	Chavez & Uchanski 2021
	Use as a fertilizer. Helps in plant or crop growth.	Schmitt & de Vries 2020
Medical field	Chitosan can be used as a wound dressing to promote the faster regeneration of skin epithelial cells and collagen production by fibroblasts.	Baharlouei & Rahman 2022
	Chitin as a drug delivery system to deliver drugs topically. Chitin can also be utilized in cancer treatment as a medium for delivering cancer medications to particular sites, and it has an antiproliferative impact by lowering cell survival.	
	Tissue engineering serves as a bone replacement for the restoration of bones, achieved through modification with hydroxyapatite or bioactive glass ceramics.	Tao et al. 2020
Water treatment	Water purification involves the use of chitin and chitosan to remove hazardous pollutants, including water-soluble organics (phenols, dyes, pesticides, herbicides) and heavy metal ions.	Chavez & Uchanski 2021

Food industry	Food preservation benefits from chitin oligosaccharides (CHOS), which possess strong antibacterial properties, making them a potential additive for combating bacterial infections and extending food shelf life. Chitin and chitosan are also used as emulsifying, fining, thickening and stabilizing agents, antioxidants, and low-calorie food mimetics.	Zhang et al. 2023
Cosmetics	Chitin and its derivatives are excellent moisturizing and anti-ageing agents that protect the skin from external hazards, improving important skin functions such as heat regulation, protection, secretion, excretion, sensation and absorption.	Morganti et al. 2006

CONCLUSIONS

In recent years, the use of black soldier flies (BSF) for managing organic waste has gained significant attention due to their ability to convert waste into valuable products. These include high-quality protein suitable for livestock and aquaculture feed, lipid for biodiesel production, and chitin, with the residual by-product serving as an effective organic fertilizer. In addition, it can help economically and can promote sustainable waste management than other technologies such as anaerobic digestion and composting. The main advantage of BSF treatment is its ability to convert a wide range of organic waste, including agricultural and food waste. Previously, BSF handling technology was in its early stages, requiring improvements in feeding strategies, genetic modifications, and large-scale farming development. However, BSF utilization has now progressed significantly, with large-scale operations successfully implemented and widely adopted. Despite some ongoing challenges, BSF farming continues to enhance the sustainability of organic waste management. The larvae of the black soldier fly show a sustainable solution and have the ability the convert organic waste into valuable resources, such as high-quality proteins for feeds, fertilizer, and fat, which can be used as renewable biodiesel sources and also can be used in cosmetics. However, there is still room to investigate new feeding substrates for BSF. This might result in the creation of fresh techniques for turning waste into useful resources. Such as genetic modification is also one of the possible and potential ways to produce strains that can show resistance to pests and diseases. This can lead to an increase in the growth rate, and the efficiency of feed conversion and can improve the quality of protein, lipid, chitin and fertilizers, and can make it more sustainable. For instance, BSF could be fed nutrient-rich foods like algae or seaweed. This might minimize the negative effects of aquaculture on the environment while also providing BSF with a fresh supply of protein and lipid. In addition, BSF offer an environmentally friendly solution for the management of waste that could help reduce our dependence, especially on fossil fuels, to protect our planet, most importantly, to face the challenges of climate change.

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Authors' Contributions
Ikram Ullah and Hadura Abu Hasan conceptualized the article, while Ikram Ullah and Muhammad Salman drafted the manuscript. Hadura Abu Hasan reviewed the paper, provided critical insights, and edited the final draft. All authors contributed to the discussion and refinement of ideas and approved the final version of the manuscript.

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