



Black Soldier Fly: A Novel Solution for Organic Waste Recycling, Alternative Protein Production, and Food Security

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ABSTRACT

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The escalating production of organic waste, the rapidly growing demand for protein for both human consumption and animal feed, and the intensifying pressure on water resources, soil, and conventional agricultural inputs have collectively underscored the urgent need for the development of low-input, biological solutions. In this regard, the black soldier fly (*Hermetia illucens*) has attracted considerable attention in recent years owing to its relatively short life cycle, its capacity to consume a wide spectrum of organic materials, and its ability to convert a significant fraction of these substrates into insect biomass. The larvae of this species are capable of transforming food waste and various organic streams into biomass that is exceptionally rich in protein and lipids, while simultaneously generating a valuable by-product known as frass. The present review examines the potential of black soldier fly-based technology, focusing on its biology and life cycle, rearing conditions, the distinction between open and closed systems, substrate and feed management, the range of harvestable products, and the insect's role within the circular bioeconomy. Furthermore, it discusses the applications of larval meal, oil, frass, and compounds such as chitin and chitosan, together with the opportunities and limitations of their utilisation in animal feed, aquaculture, agriculture, and biotechnology. Within the conceptual framework derived from current research, the black soldier fly should not be viewed exclusively as a waste management tool; rather, it can be conceived as an intrinsic element of a closed-loop system wherein waste is transformed into biomass and subsequently into feed, fertiliser, and other high-value products. However, factors including substrate safety, consistency in feed composition, production costs, standardisation, regulatory frameworks, pathogen control, and market acceptance constitute the most critical obstacles to the industrial-scale deployment of this technology. In Iran, establishing clear standards, advancing indigenous technical expertise, creating sustainable supply chains, and conducting research adapted to the local climate and socio-economic context can facilitate the responsible expansion of this nascent industry.

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Introduction

The rapid growth of population, urbanisation, and changing consumption patterns has substantially increased the generation of organic waste and intensified concerns regarding waste management, resource depletion, and food security. At the same time, the increasing demand for protein-rich feed ingredients has placed considerable pressure on conventional sources such as soybean meal and fishmeal. The production of these resources is associated with environmental challenges, including deforestation, overfishing, high water consumption, and greenhouse gas emissions. Consequently, increasing attention has been directed toward alternative protein sources that can simultaneously contribute to organic waste valorisation and resource recovery. Among emerging biological technologies, the black soldier fly (BSF), *Hermetia illucens*, has received considerable attention because of its high capacity to convert diverse organic substrates into valuable biomass. BSF larvae can consume food waste, agricultural residues, and manure and convert them into protein- and lipid-rich biomass, while the remaining frass can be used as a nutrient-rich agricultural amendment. This characteristic makes BSF particularly relevant to circular economy and sustainable agriculture approaches. In addition to larval meal, BSF production can provide oil, frass, chitin, chitosan, and bioactive compounds with potential applications in animal feed, agriculture, industry, and biotechnology. Although BSF technology has progressed considerably at the global level, its development in Iran remains constrained by technical, regulatory, economic, and market-related challenges. Therefore, this study aimed to review the biological characteristics, rearing requirements, production systems, products and applications, circular-economy potential, and major opportunities and limitations associated with BSF production, with particular emphasis on its prospects for development in Iran.

Method

A descriptive and analytical review was conducted on the biology, production, applications, sustainability, and development prospects of *H. illucens*. The available evidence was synthesised thematically according to major components of the BSF production chain. The review considered the biological and developmental characteristics of BSF, environmental and operational requirements including temperature, humidity, substrate properties, moisture, and larval density, and differences between open and closed production systems in terms of environmental control, investment, biosecurity, and scalability. Major products, including larval protein meal, oil, frass, chitin, chitosan, and bioactive compounds, were examined alongside their potential applications. The circular-economy potential of BSF was assessed through organic-residue conversion, feed production, and nutrient recycling. Finally, opportunities and limitations for BSF development in Iran were reviewed, including substrate availability, dependence on imported feed ingredients, research activities, emerging businesses, regulatory conditions, technical capacity, product safety, and market barriers.

Results

The review demonstrated that BSF has considerable potential to integrate organic waste valorisation with alternative protein production. Successful production depends strongly on environmental and nutritional conditions. Under favourable conditions, particularly temperatures of approximately 27–32°C and relative humidity of 60–80%, eggs hatch within 3–4 days and larvae can reach harvestable size within approximately 14–21 days. Substrate characteristics strongly influence larval growth, biomass yield, and product quality. A moisture content of approximately 60–70% is generally suitable for larval development, while substrate composition affects biomass composition; protein-rich substrates may support growth, whereas starch-rich substrates can promote lipid accumulation. Appropriate feeding and larval-density management are therefore essential to avoid anaerobic conditions, odour generation, and

reduced productivity. Production systems differ according to scale and resource availability. Open systems generally require lower investment and may be suitable for small-scale or rural applications, but limited environmental and biosecurity control can reduce consistency and scalability. Closed systems require greater investment but allow better control of temperature, humidity, lighting, feeding, and harvesting, making them more suitable for standardised and industrial production. Automation of feeding, environmental control, and harvesting may further improve efficiency and consistency.

BSF biomass has multiple potential applications. Depending on substrate and processing conditions, dried larvae may contain approximately 40–45% protein and 15–25% fat, with a useful amino acid profile. This supports their potential as a partial alternative to conventional protein sources, particularly fishmeal, in aquaculture and poultry feed. BSF oil, characterised by its high lauric acid content, has potential applications in feed, biodiesel, and cosmetics. Frass contains nutrients and organic matter and may contribute to soil fertility and plant growth; however, its commercial use requires control of composition and microbiological safety. Chitin and chitosan obtained from larval cuticles also have potential applications in agriculture, medicine, drug delivery, and biodegradable materials. Bioactive compounds, including antimicrobial peptides, represent additional opportunities, although further safety and efficacy studies are required. BSF production is closely aligned with circular-economy principles because it converts organic residues into protein and lipid biomass while returning nutrients to agricultural systems through frass. Nevertheless, environmental and economic benefits are context-dependent and may be affected by energy and water consumption, transportation, substrate preparation, drying, and processing. Life-cycle and economic assessments are therefore necessary to evaluate sustainability under specific conditions.

In Iran, the availability of agricultural, food, and municipal organic residues and dependence on imported protein feed ingredients provide opportunities for BSF development. Iranian universities have increasingly investigated local substrates, larval growth, and nutritional characteristics, while emerging businesses and pilot projects have explored training, farm design, equipment, and insect production. However, wider adoption is limited by the absence of comprehensive national standards and clearly defined regulations for insect production, substrate use, and feed applications. Limited technical knowledge, inadequate training and extension services, uncertain market demand, and economic competitiveness also remain important constraints. Product safety requires particular attention because unsuitable substrates may introduce heavy metals, mycotoxins, pharmaceutical residues, or pathogens, while variations in substrate, larval age, and processing can result in inconsistent product quality.

Conclusions

BSF technology offers an integrated approach to organic waste valorisation, alternative protein production, and nutrient recycling within a circular bioeconomy. Its ability to convert diverse organic residues into protein- and lipid-rich biomass, together with valuable products such as frass, oil, chitin, and chitosan, creates opportunities for agricultural and industrial applications. In Iran, abundant organic residues and the need for alternative domestic feed ingredients provide a basis for further development. However, technological potential alone is insufficient for industrial adoption. National standards, clear regulatory frameworks, improved technical and extension capacities, pilot and demonstration facilities, and context-specific economic and life-cycle assessments are required. Future research should prioritise production optimisation, automation, selective breeding, substrate safety, product standardisation, and integration with waste-management systems. Collaboration among researchers, industry, policymakers, and standard-setting organisations will be essential for developing a safe, economically viable, and sustainable BSF sector in Iran.

نتیجه‌گیری

مگس سرباز سیاه به‌عنوان یک راهکار زیستی امیدبخش، ظرفیت قابل‌توجهی برای تلفیق ارزش‌افزایی پسماندهای آلی، تولید پروتئین جایگزین و بازیافت مواد مغذی در چارچوب اقتصاد زیستی چرخشی دارد. بررسی شواهد موجود نشان می‌دهد که لاروهای این گونه می‌توانند طیف متنوعی از بسترهای آلی مناسب را به زیست‌توده‌ای غنی از پروتئین و چربی تبدیل کنند و در کنار آن، فرآورده‌های باارزشی مانند فرس، روغن، کیتین و کیتوزان تولید نمایند. با این حال، کارایی و ایمنی این سامانه به عواملی همچون کیفیت بستر، شرایط محیطی، مدیریت پرورش، روش‌های فرآوری و اجرای نظام‌های مناسب کنترل کیفیت وابسته است (Lai-Foenander et al., 2024; Lock et al., 2015).

در ایران، وجود مقادیر قابل‌توجهی از پسماندهای کشاورزی و صنایع غذایی، در کنار افزایش نیاز به منابع پروتئینی جایگزین، زمینه مناسبی برای توسعه فناوری مگس سرباز سیاه فراهم می‌کند. افزایش فعالیت‌های پژوهشی دانشگاهی و شکل‌گیری برخی فعالیت‌های تجاری و دانش‌بنیان نیز نشان‌دهنده رشد توجه علمی و اقتصادی به این فناوری است. با این حال، گذار از تولید آزمایشگاهی و مقیاس کوچک به یک صنعت پایدار و قابل‌اعتماد، نیازمند توجه جدی‌تر به ایمنی بستر، استانداردسازی فرآیند تولید، کنترل کیفیت محصولات، توجیه‌پذیری اقتصادی و تدوین چارچوب‌های نظارتی است.

از این‌رو، پژوهش‌های آینده باید بر بهینه‌سازی و خودکارسازی سامانه‌های پرورش، ارزیابی بسترهای آلی بومی، بهبود عملکرد زیستی و اصلاح نژاد، بررسی دقیق ایمنی و کیفیت تغذیه‌ای محصولات و تدوین پروتکل‌های استاندارد برای زیست‌توده لارو و فرس متمرکز شوند. همچنین، انجام ارزیابی چرخه حیات و مطالعات اقتصادی متناسب با شرایط ایران برای تعیین عملکرد واقعی زیست‌محیطی و اقتصادی سامانه‌های مختلف ضروری است. ایجاد استانداردهای ملی و چارچوب‌های قانونی شفاف، همراه با تقویت آموزش‌های تخصصی و همکاری میان دانشگاه‌ها، صنعت، سیاست‌گذاران و نهادهای نظارتی، از الزامات توسعه مسئولانه این حوزه خواهد بود. در مجموع، مگس سرباز سیاه را نباید صرفاً به‌عنوان یک منبع پروتئینی جایگزین در نظر گرفت، بلکه می‌توان آن را به‌عنوان یکی از اجزای یک سامانه یکپارچه برای ارزش‌افزایی پسماند، بازیافت منابع و تولید پایدار در ایران مورد توجه قرار داد.

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