

REVIEW ARTICLE

From Waste to Bio-Economy: A Review on Black Soldier Fly (*Hermetia Illucens*) – Biology, Bioconversion and Indian Perspectives

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ABSTRACT

The Black Soldier Fly (BSF), *Hermetia illucens*, has emerged as a promising solution for sustainable waste management and resource recovery. Its larvae efficiently convert various organic wastes including food scraps, crop residues, and animal manure into high-value products such as protein-rich meal, lipid-rich oil, and nutrient-dense frass. This transformation supports a circular bio-economy by linking waste reduction, animal feed production, and soil health. The BSF is a holometabolous insect whose larval stage is critical for bioconversion. Successful rearing requires optimal conditions: temperatures of 27–32°C, relative humidity between 60–80%, and specific light and odour cues that regulate reproduction. Additionally, its gut microbiome plays a vital role in enhancing digestion, reducing odour, and suppressing pathogens. Globally, BSF farming has seen significant growth. The European Union allows BSF-derived ingredients in feeds for aquaculture, poultry, and swine, while the United States permits BSF meal and oil in animal nutrition. In Asia, countries like China, Vietnam, and Singapore have integrated BSF into food security and aquaculture systems. Beyond animal feed, BSF offers potential in sectors such as bioplastics, pharmaceuticals, cosmetics, and biodiesel through the extraction of chitin, chitosan, peptides, and oils. In India, institutions like ICAR–NBAIR and ICAR–CIBA, alongside start-ups, are advancing BSF research and commercialization. The country's tropical climate and abundant waste make it ideal for BSF adoption, though regulatory gaps, particularly the absence of BIS standards for frass, remain a challenge. With targeted policy support, scientific innovation, and farmer awareness, BSF can play a pivotal role in India's sustainable development and food system resilience.

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INTRODUCTION

The world is facing a serious problem of waste generation and food security. Every year, large amounts of food, agricultural residues, and animal manure are produced. These wastes pose disposal challenges and contribute to increased greenhouse gas emissions. At the same time, there is a growing demand for protein for aquaculture, poultry, livestock, and the pet industries. The global population is expected to exceed 9.7 billion by the year 2050. This will put tremendous pressure on food systems, protein supply, and waste management. Conventional protein sources such as soybean meal and fishmeal are limited. They are linked to environmental issues such as deforestation, overfishing, and climate change (Van Huis, 2020).

In this context, the Black Soldier Fly (*Hermetia illucens*) has emerged as an important insect species. It is a non-pest fly belonging to the family Stratiomyidae. The larvae of the Black Soldier Fly (BSF) can convert a wide variety of organic wastes into valuable products. These products include protein rich larval meal, oil, chitin, and frass. Frass is the residue left behind after larval feeding. It contains nutrients and beneficial microbes and can be used as an organic fertiliser (Salomon, 2025; Beesigamukama et al., 2020).

From Waste Management to Circular Economy

Early studies on BSF focused on using the larvae for manure management. Researchers have shown that BSF larvae can reduce the volume of organic waste, control odors, and suppress harmful pathogens (Sheppard et al., 1994; Erickson et al., 2004). Over time, the scope of research expanded. Scientists began to study the nutritional value of BSF larvae. It was found that the larvae contain 40–45% protein and 25–35% lipids on a dry matter basis (Lu et al., 2022). These values make the BSF meal a strong alternative to fishmeal and soybean meal.

The idea of the “circular bio-economy” has gained importance in recent years. In this model, waste materials are not discarded but are used again to produce valuable products. BSF fits well into this model. It reduces waste, produces alternative protein, and returns nutrients to the soil through frass. Additionally, BSF-derived chitin and bioactive compounds present new opportunities in pharmaceuticals, bioplastics, and animal health (Müller et al., 2017; Zhou et al., 2022).

Biology and Environmental Suitability

The BSF has a complete life cycle with egg, larva,

pupa, and adult stages. The larval stage is the most important for waste conversion. Females lay eggs in dry crevices near decomposing organic matter. Larvae hatch and feed aggressively for 14–18 days before pupation. Adults do not feed; their primary function is reproduction (Tomberlin and Sheppard, 2002). Temperature, humidity, light, and larval density strongly affect development and survival. BSF is well-suited for tropical and subtropical climates, making India an ideal location for its mass rearing (Diener et al., 2009).

Advances in Science and Technology

In the last decade, research on BSF has moved from applied waste management to advanced science. High-quality genome assemblies of BSF have been published (Generalovic et al., 2021; Van Huis, 2020; Cai et al., 2024). These resources allow selective breeding and genomic studies to improve traits such as feed conversion efficiency, growth rate, and stress tolerance. Transcriptomic studies have revealed how BSF responds to diet, temperature, and microbial exposure (Kariuki et al., 2023).

The gut microbiome of BSF also plays a vital role in waste digestion and pathogen suppression (Jeon et al., 2011). Researchers are now exploring probiotics and microbial inoculants to stabilise production (Wang and Shelomi, 2017). Sensory biology studies have identified light spectra and fatty acids such as tetradecanoic acid as key cues for mating and oviposition (Klüber et al., 2024). These findings are helpful in designing colony management systems for indoor mass rearing.

Global Industry and Regulation

The global BSF industry is experiencing rapid expansion. The Association of American Feed Control Officials (AAFCO) has approved BSF meal and oil as ingredients for poultry, aquaculture, and pets (Banks et al., 2025). The European Union has permitted the use of BSF proteins in aquaculture feeds since 2017 and expanded approval to poultry and pig feeds in 2021 (European Commission, 2021). Singapore has also recognised BSF as part of its food security plan.

The global BSF market is projected to reach USD 3–5 billion by 2032. Companies in Europe, North America, and Asia are building industrial-scale facilities. These developments demonstrate that BSF is not only a research subject but also a commercially

viable solution for sustainable protein and waste management (Zion Market Research, 2023).

Indian Perspectives

In India, BSF research and application are still in the early stages but growing rapidly. The Indian Council of Agricultural Research – National Bureau of Agricultural Insect Resources (ICAR–NBAIR) in Bengaluru has established a mass-rearing unit and provides starter colonies (ICAR–NBAIR, 2022). The Central Institute of Brackishwater Aquaculture (ICAR–CIBA) in Chennai has tested BSF meal as an ingredient in shrimp diets, yielding positive results (ICAR–CIBA, 2023). Several start-ups, including Loopworm (Bengaluru), Insectifii (Pune), and Grub Cycle (Hyderabad), are developing large-scale production facilities.

Despite this progress, challenges remain. India does not yet have Bureau of Indian Standards (BIS) guidelines for frass. Food safety regulations for human consumption are not defined. Further research is needed to establish quality standards, develop breeding programs, and identify effective microbial inoculants. However, India's tropical climate and abundant organic waste streams make it uniquely suited for BSF farming. With proper policy support, BSF can become a cornerstone of India's bio-economy.

BIOLOGY AND LIFE HISTORY OF BLACK SOLDIER FLY (*Hermetia illucens*)

The Black Soldier Fly (BSF), *Hermetia illucens* (Diptera: Stratiomyidae), is one of the most studied insects for waste recycling and protein production. It is a holometabolous insect, which means it has four stages in its life cycle: egg, larva, pupa, and adult. Each stage has special features and ecological importance. The biology of BSF makes it well-suited for converting waste into valuable biomass. Its short life cycle, high larval feeding rate, and ability to thrive in tropical climates have made it a model insect for bio-economy research (Diener *et al.*, 2009).

Egg Stage

Female BSF lay eggs in clusters, usually 200–600 eggs at one time. The eggs are creamy white and very small, measuring about 0.9–1.2 mm in length. Females prefer to lay eggs in dry cracks or crevices near decomposing organic matter, but not directly on the waste. This strategy protects the eggs from being drowned or eaten by other insects. Eggs usually hatch within 2–4 days under warm tropical conditions (Sheppard *et al.*, 1994).

Odours from organic substrates influence the choice of oviposition site. Studies have shown that fatty acids, such as tetradecanoic acid, stimulate egg laying. Females are selective and lay eggs close to moist substrates that can support larval growth (Klüber *et al.*, 2024). The survival and hatching rate of eggs depend on humidity and temperature. Relative humidity above 60% is ideal for proper hatching (Tomberlin and Sheppard, 2002).

Larval Stage

The larval stage is the most critical phase for waste bioconversion. After hatching, larvae feed aggressively on organic material. They pass through six instars and grow rapidly, reaching a length of 15–20 mm and a weight of up to 200 mg. This stage lasts 14–18 days under tropical conditions but may extend longer in cooler environments (Diener *et al.*, 2009).

Larvae contain 40–45% protein and 25–35% lipids on a dry matter basis. The protein fraction is rich in essential amino acids. The oil fraction contains lauric acid, which has antimicrobial properties. This makes BSF larvae a useful feed source for poultry, pigs, and fish (Lu *et al.*, 2022). During feeding, larvae can reduce waste volume by 50–80%. They suppress pathogens such as *Escherichia coli* and *Salmonella* by outcompeting them in the substrate (Erickson *et al.*, 2004). The larval gut microbiome also plays a role in digestion and pathogen control. Bacteria like *Lactobacillus* and *Bacillus* dominate and contribute to waste degradation (Jeon *et al.*, 2011).

Prepupal Stage

When larvae complete their feeding, they stop eating and enter the prepupal stage. The body colour changes from cream to dark brown as the cuticle hardens. The prepupae migrate away from the food source in search of dry pupation sites. This behaviour is used in farming systems for self-harvesting. Special ramps or collection devices guide prepupae into containers, reducing labour costs (Sheppard *et al.*, 1994). Prepupae have the highest energy reserves. They contain more lipids than younger larvae. This makes them ideal for feed and oil extraction. In natural ecosystems, prepupae provide a nutrient-rich food source for birds, reptiles, and other animals (Newton *et al.*, 1997).

Pupal Stage

The pupal stage is a non-feeding, resting stage.

Inside the hardened exoskeleton, the larva undergoes a transformation into an adult. This process takes 8–10 days, depending on temperature and humidity. Pupae are usually found in dry soil, litter, or protected crevices. They are dark brown to black in colour and measure about 10–15 mm in length. The pupal stage ensures survival during unfavourable conditions. It allows the insect to withstand environmental stress until emergence. Pupae are not usually used in farming systems, but they play a natural role in recycling nutrients into the soil (Diener *et al.*, 2009).

Adult Stage

Adult BSF resemble wasps but are harmless and do not sting. They are black with metallic reflections and have long legs. Adults live for 5 to 8 days. They do not feed but rely on fat reserves stored during the larval stage. Their primary role is reproduction. Mating usually occurs in bright light. Blue and green light wavelengths are critical. In colony management, providing artificial light of the correct spectrum helps increase mating success (Tomberlin and Sheppard, 2002). After mating, females lay eggs and die soon after. Males patrol territories and attempt to mate with females in flight. Because adults do not feed, they are not vectors of disease. This makes BSF safer compared to houseflies. Their presence reduces housefly populations, since BSF larvae consume waste that would otherwise attract pest flies (Sheppard *et al.*, 1994).

Environmental Factors Affecting Development

Temperature, humidity, and photoperiod are crucial for the development of BSF. Optimal temperature is 27–32 °C. Lower temperatures slow growth and increase mortality. A relative humidity of 60–80% is required for egg hatching and larval survival. Photoperiod influences mating and oviposition. A light regime of 12–14 hours with proper intensity promotes reproductive success (Diener *et al.*, 2009). Substrate quality also influences growth. Protein-rich substrates produce larger larvae, while carbohydrate-rich substrates produce larvae with more fat. Moisture content between 60–70% is ideal. Very wet substrates cause larval drowning, while dry substrates reduce feeding efficiency (Camille *et al.*, 2020).

Significance of Biology for Farming

Understanding the life history of BSF is essential for large-scale production. Each stage requires different environmental and management conditions.

Egg collection devices, optimised substrates, and self-harvesting systems improve efficiency. Colony management also depends on light conditions and chemical cues for oviposition. Breeding programs aim to enhance traits such as growth rate, survival, and waste conversion efficiency (Van Huis, 2020). The biological traits of BSF make it a unique insect for the circular economy. It grows quickly, converts waste efficiently, and provides safe, high-quality protein. Its biology also reduces risks because adults do not feed or transmit diseases. For these reasons, BSF has become a global focus for sustainable agriculture, animal feed, and waste management.

ENVIRONMENTAL REQUIREMENTS AND COLONY MANAGEMENT

The Black Soldier Fly (*Hermetia illucens*) is now widely reared across the world. Its successful farming depends on the proper management of environmental conditions. The insect is sensitive to temperature, humidity, light, and the quality of its substrate. Each stage of the life cycle requires specific conditions for survival and productivity. Good colony management also needs careful planning of oviposition, larval rearing, and harvesting systems. In this section, the environmental requirements and management practices for efficient BSF production are explained.

Temperature

Temperature is the most critical factor in BSF farming. The optimum range for development is 27–32 °C. Within this range, egg hatching, larval feeding, and pupation are successful. At lower temperatures below 20 °C, the life cycle becomes longer and survival decreases. At very high temperatures above 35 °C, egg and larval mortality increase (Diener *et al.*, 2009). Larval growth is fastest between 27 °C and 30 °C. Adults also show more mating activity at this range. In controlled indoor systems, heaters or cooling units are used to maintain the correct temperature. In tropical countries like India, natural conditions are already favourable for BSF rearing (Sheppard *et al.*, 1994).

Humidity

Relative humidity plays a role in egg hatching and larval survival. The ideal humidity is between 60% and 80%. At low humidity, eggs dry out and fail to hatch. At very high humidity levels above 90%, fungal growth may occur in the substrate, reducing larval performance

(Tomberlin and Sheppard, 2002). Humidity also affects pupation. Prepupae migrate away from moist waste and pupate in drier environments. In indoor facilities, humidifiers and ventilation fans are used to regulate moisture. In open systems, farmers must avoid waterlogging of the substrate. Proper drainage in rearing containers is essential to prevent drowning of larvae (Diener *et al.*, 2009).

Light

Light is essential mainly for adults. They depend on specific light intensities and wavelengths for mating and oviposition. Studies show that blue and green light spectra are the most effective. Without proper light, adults will not mate, and egg production will stop (Tomberlin and Sheppard, 2002). In indoor farms, artificial lighting systems are used. This mimics natural sunlight and provides 12–14 hours of light daily. Light intensity must be maintained at levels that allow natural mating behaviour. Modern rearing facilities use LED lights, which are energy-efficient and effective for stimulating reproduction (Klüber *et al.*, 2024).

Oviposition Management

Female BSF prefer to lay eggs near decomposing organic matter. They deposit eggs in cracks, crevices, or artificial traps placed above substrates. Semiochemicals, such as tetradecanoic acid and other fatty acids, stimulate egg laying (Klüber *et al.*, 2024). In colony management, oviposition devices are used. These are wooden or cardboard strips with small slots where females deposit eggs. The devices are placed above moist feed material. Eggs can be collected from these devices and transferred to larval rearing trays for further development. This system ensures good yield and prevents egg loss in the substrate.

Substrate Quality and Moisture

The substrate used for rearing larvae must provide a balance of nutrients and moisture. Larvae can grow on a wide variety of wastes, including food scraps, animal manure, and crop residues. However, growth is better in substrates with a moisture level of 60–70%. Very wet substrates cause drowning and foul odours. Very dry substrates reduce larval feeding and slow down growth (Camille *et al.*, 2020). Farmers often mix different substrates to improve nutrition. Protein-rich wastes, such as fish or meat residues, increase larval protein content. Starchy wastes, such as brewery by-products, increase fat deposition. Microbial inoculants, such as *Lactobacillus*, are sometimes

added to enhance digestion and reduce the presence of pathogens (Jeon *et al.*, 2011).

Larval Density and Feeding Rate

Larval density affects growth and conversion efficiency. If too many larvae are reared together, competition for food increases, and growth is reduced. If density is too low, the feed is under-utilised. An optimum density of 5–10 larvae per gram of substrate is often recommended (Diener *et al.*, 2009). Feeding rates also depend on the type of substrate. High-energy wastes require lower feeding rates. Farmers adjust feeding by monitoring waste reduction and larval weight gain to optimize production. Overfeeding can lead to anaerobic conditions and unpleasant odours, while underfeeding reduces larval yields.

Colony Management in Indoor Systems

Indoor BSF farming provides better control over environmental conditions. Modern systems include climate-controlled rooms, artificial lighting, and automatic feeding. Eggs are collected using oviposition traps and transferred to hatching trays. Newly hatched larvae are moved to larger trays for feeding. After two weeks, prepupae are harvested using self-collection ramps. Indoor systems also use microbiome management. Beneficial bacteria are added to reduce odours and improve waste breakdown (Wang and Shelomi, 2017). Selective breeding programs are being developed to improve colony stability and productivity (Van Huis, 2020).

Colony Management in Outdoor Systems

Outdoor systems are simpler and less expensive, but more susceptible to weather conditions. They are common in tropical countries where temperatures are naturally suitable. Waste is placed in open bins or trenches. Adult flies mate in the open, and females lay eggs near the waste. Larvae develop in the waste until they reach the prepupal stage. Harvesting is done by collecting migrating prepupae. Outdoor systems require less investment but produce lower yields. They are helpful for small-scale farmers and waste recycling projects in rural areas (Sheppard *et al.*, 1994).

Biosecurity and Hygiene

Colony management must include biosecurity practices. Although BSF larvae suppress many pathogens, poor management can still create risks. Farmers must ensure that only safe organic wastes

are used. Toxic or chemical-contaminated wastes should be avoided. Containers and equipment must be cleaned regularly to maintain cleanliness. Proper drying and processing of larvae and frass are necessary before use in feed or fertiliser (Bruno *et al.*, 2025).

Importance of Environmental Management

Maintaining the proper environment is essential for large-scale BSF production. Temperature, humidity, and light influence the success of each life stage. Substrate quality, larval density, and microbial interactions affect productivity. Proper colony management enhances waste reduction, larval yield, and product quality. Advances in indoor systems, microbiome science, and breeding are helping BSF become a reliable component of sustainable agriculture.

WASTE BIOCONVERSION AND PRODUCT STREAMS

The Black Soldier Fly (*Hermetia illucens*) has the unique ability to convert organic wastes into valuable products. Its larvae feed on a wide range of substrates, including food waste, manure, crop residues, and agro-industrial by-products. During feeding, the larvae reduce waste volume, control odours, and suppress harmful microbes. At the same time, they produce biomass rich in protein, oil, and other valuable compounds. The residue left behind, known as frass, can be used as an organic fertiliser. Due to these qualities, BSF is now recognized as a key insect for waste valorization and the circular bioeconomy.

Types of Wastes Recycled by BSF

Black soldier fly (BSF) larvae can grow on many kinds of organic materials. These include food waste from households, markets, and restaurants; animal manure, such as poultry, pig, and cattle manure; agro-industrial residues, like brewery by-products, fruit pulp, oilseed cakes, and sugar-industry waste; and crop residues, including damaged fruits, vegetables, and other perishable produce. Research shows that BSF larvae can reduce the volume of these wastes by 50–80%, which helps solid waste management and lowers the load on landfills (Diener *et al.*, 2011).

Waste Reduction and Pathogen Control

One of the significant benefits of BSF is its ability to suppress harmful pathogens. During feeding, BSF larvae outcompete bacteria such as *Escherichia coli* and *Salmonella*. Studies found that these pathogens decrease significantly in substrates with active BSF

larvae (Erickson *et al.*, 2004; Lalander *et al.*, 2013; Oonincx *et al.*, 2015). This property makes BSF useful for manure management and safer recycling of wastes. The larvae also reduce foul odours from decomposing wastes. Their rapid feeding prevents the growth of houseflies and other pests. In fact, BSF farming is seen as an eco-friendly alternative to chemical or mechanical waste treatment methods (Sheppard *et al.*, 1994; Yuan and Hasan, 2022).

BSF Protein Meal

The most valuable product of BSF farming is larval meal. Dried larvae or prepupae are processed into powder and used as a protein source in animal feed. On a dry matter basis, BSF meal contains 40–45% protein and has a well-balanced amino acid profile. It is especially rich in lysine and methionine, which are essential for poultry and fish (Lu *et al.*, 2022). In aquaculture, BSF meal is tested as a replacement for fishmeal. Fishmeal is expensive and unsustainable, as it comes from overfished oceans. The BSF meal offers a cheaper and eco-friendly option. Trials with tilapia and shrimp have shown good growth performance when fed diets containing BSF meal (Henry *et al.*, 2015). For poultry and pigs, BSF meal improves feed efficiency and growth. It also enhances gut health due to its antimicrobial properties. In pets, BSF-based diets are marketed as hypoallergenic and sustainable alternatives to conventional feeds (Lock *et al.*, 2015).

BSF Oil

BSF larvae also produce oil, which makes up 25–35% of their dry weight. The oil is rich in lauric acid, a fatty acid with antimicrobial and antiviral properties. This makes BSF helpful oil not only for animal feed but also for health applications. In animal nutrition, BSF oil can replace vegetable oils and fish oil in poultry and aquaculture diets. Studies have shown that BSF oil improves gut microbiota and reduces the presence of harmful bacteria in animals (Makkar *et al.*, 2014). BSF oil is also explored for biodiesel production. Its fatty acid composition is similar to coconut oil, making it a renewable energy source. Additionally, the cosmetic industry is testing BSF oil for use in skin and hair care products.

BSF Frass

Frass is the residue left after larval feeding. It contains undigested food, larval excreta, and shed skins. Frass is rich in nitrogen, phosphorus, and

potassium, as well as beneficial microbes. It can be used as an organic fertiliser to improve soil fertility (Beesigamukama *et al.*, 2020). Studies show that frass improves plant growth and reduces soil-borne pests and diseases. In tomato cultivation, the application of BSF frass increased yield and improved soil microbial diversity (Parra-Pacheco *et al.*, 2025). Despite its potential, the use of frass faces challenges. Quality standards are not yet defined in many countries, including India. Regulatory authorities are still studying its safety and consistency. The development of national standards will be crucial for the commercial use of BSF frass.

Chitin and Chitosan

BSF larvae and pupal cases are sources of chitin, a natural polymer. Chitin can be extracted and processed into chitosan. These compounds have a wide range of applications in agriculture, medicine, and industry. In agriculture, chitin and chitosan are utilized as biostimulants to promote plant growth and enhance resistance. In medicine, they are used for wound dressings, drug delivery, and antimicrobial materials. In industry, they are explored for the production of biodegradable plastics (Müller *et al.*, 2017). The advantage of BSF over crustacean sources is that it provides chitin as a by-product of waste bioconversion. This reduces dependency on shrimp and crab shells.

Bioactive Compounds

BSF larvae also produce antimicrobial peptides and bioactive lipids. These compounds show activity against harmful microbes and oxidative stress. Research is ongoing to identify and characterise these molecules for pharmaceutical and veterinary use (Boccazzi *et al.*, 2017; Zhou *et al.*, 2022). Bioactive compounds from BSF may become new alternatives to antibiotics in animal production. They may also find uses in human medicine for treating infections.

Economic and Environmental Benefits

Waste conversion by BSF provides both economic and ecological benefits. Farmers and industries can save money on waste disposal. They also obtain valuable products such as protein meal, oil, and fertiliser. For developing countries, BSF farming provides new income opportunities and employment (Kariuki *et al.*, 2023). Environmentally, BSF reduces waste in landfills, lowers greenhouse gas emissions, and recycles nutrients. It is a nature-based solution for sustainable farming and waste management.

Challenges in Product Development

Although BSF products show promise, challenges remain. Standardization of frass quality is lacking. Regulations for using BSF products in food and feed are still evolving. Processing methods for oil, chitin, and peptides need further development. Public acceptance is also a challenge, especially for insect-based food products. Future research must focus on improving product safety, efficiency, and market value. International guidelines and local standards are necessary for scaling the industry.

CHALLENGES, RESEARCH GAPS, AND FUTURE PROSPECTS

The Black Soldier Fly (*Hermetia illucens*) has emerged as a promising solution for waste management and sustainable protein production. Its larvae convert organic waste into protein, oil, and fertiliser, supporting the circular bio-economy. However, despite global progress, several challenges and research gaps remain. Addressing these issues is essential worldwide.

Challenges in BSF Farming

Lack of Standards

One of the biggest challenges is the absence of clear quality and safety standards. In India, there are no Bureau of Indian Standards (BIS) guidelines for BSF frass, protein meal, or oil. Without standards, industries and farmers face difficulties in marketing products. International trade is also affected because buyers demand certified quality (Beesigamukama *et al.*, 2020).

Regulatory Uncertainty

Many countries, including India, lack clear policies for insect farming. In the European Union and the United States, BSF meal is approved for aquaculture and poultry feeds. However, in India, the Food Safety and Standards Authority of India (FSSAI) has yet to provide approvals. This regulatory gap slows investments and industry growth (European Commission, 2021).

Limited Awareness and Training

BSF farming is still new for most farmers and entrepreneurs in India. Many people are unaware of the benefits of BSF products or the methods of colony management. Training programs are limited, and extension systems have not yet included BSF farming. This knowledge gap prevents widespread adoption (ICAR-NBAIR, 2022).



Technical Difficulties

Maintaining colonies on a large scale requires proper management of light, humidity, and substrate. Farmers often struggle with low egg yields, uneven larval growth, or poor substrate conversion. Indoor farms need investments in lighting and climate control. Outdoor farms face risks from weather and predators (Tomberlin and Sheppard, 2002).

Market Development

Although BSF products have potential, the market is not fully developed. The aquaculture and poultry industries are cautious about adopting BSF meal without conducting long-term feeding trials. Frass lacks a defined market due to the absence of standards. Human food applications remain limited due to safety concerns and low consumer acceptance (Van Huis, 2020).

Research Gaps

Standards for Frass and Products

There is an urgent need to develop BIS standards for frass, protein meal, and oil. Research should focus on defining the nutrient content, microbial safety, and limits on heavy metals. This will provide confidence to farmers and buyers.

Selective Breeding and Seed-Stock Development

Currently, most BSF farming in India utilizes wild-collected colonies. There are no improved seed-stock lines. Selective breeding programs are necessary to develop high-yielding strains that are adapted to Indian conditions. Traits like faster growth, higher protein content, and better climate tolerance can be improved through breeding (Van Huis, 2020).

Microbiome-Based Inoculants

The gut microbiome of the BSF plays a role in digestion and pathogen suppression. However, this area is under-researched in India. Developing probiotics or microbial inoculants can improve larval growth and waste conversion. Research should link microbiome management with substrate design (Jeon *et al.*, 2011).

Cue-Engineered Oviposition Systems

Female BSF rely on visual and chemical cues to lay eggs. Low-cost oviposition systems utilizing fatty acids, such as tetradecanoic acid or myristic acid, can enhance egg yields. India needs research on cue-engineered traps adapted to tropical conditions (Klüber *et al.*, 2024).

Biosafety Protocols

Biosecurity in BSF farms is still weak. Research should establish protocols for pathogen monitoring, validated kill steps, and safe waste handling. Studies should investigate various processing methods, such as boiling, steaming, or fermentation, to assess their effectiveness in removing pathogens (Bruno *et al.*, 2019).

CONCLUSION

The Black Soldier Fly (*Hermetia illucens*) stands at the intersection of entomology and sustainability. What was once a biological curiosity has now evolved into a powerful tool for addressing some of the most pressing global challenges, including organic waste management, protein insecurity, and declining soil fertility. The larvae of this insect efficiently convert a wide range of organic waste into valuable products such as protein-rich meal, lipid-rich oil, and nutrient-dense frass. These outputs align with the core principles of a circular bio-economy, offering environmentally responsible alternatives for feed, fertilizer, and bio-based materials.

Across the globe, the Black Soldier Fly is being increasingly adopted as part of mainstream agricultural and waste management systems. Countries in Europe and North America have approved BSF-based products for use in aquaculture, poultry, and pet feeds, while Asian nations such as China, Vietnam, and Singapore have incorporated BSF farming into their food security and waste valorization strategies. This growing acceptance reflects the global relevance of BSF in achieving sustainable development goals.

Scientific progress has further enhanced the potential of BSF farming. Insights into BSF behavior, gut microbiomes, and molecular biology have led to improved rearing practices, selective breeding, and extraction of high-value compounds like chitosan, antimicrobial peptides, and beneficial fatty acids. These developments have opened up opportunities in pharmaceuticals, bioplastics, and cosmetics.

In India, despite promising developments by institutions like ICAR-NBAIR and ICAR-CIBA, challenges remain. The absence of Bureau of Indian Standards (BIS) guidelines, regulatory uncertainty, technical constraints, and low market awareness hinder large-scale adoption. However, India's abundant organic waste, tropical climate,

and growing demand for alternative protein provide a strong foundation.

With focused policy support, targeted research, and enterprise development, BSF farming can help India transition towards a resilient circular economy. It has the potential to reduce waste, generate employment, enhance food security, and contribute meaningfully to sustainable development.

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