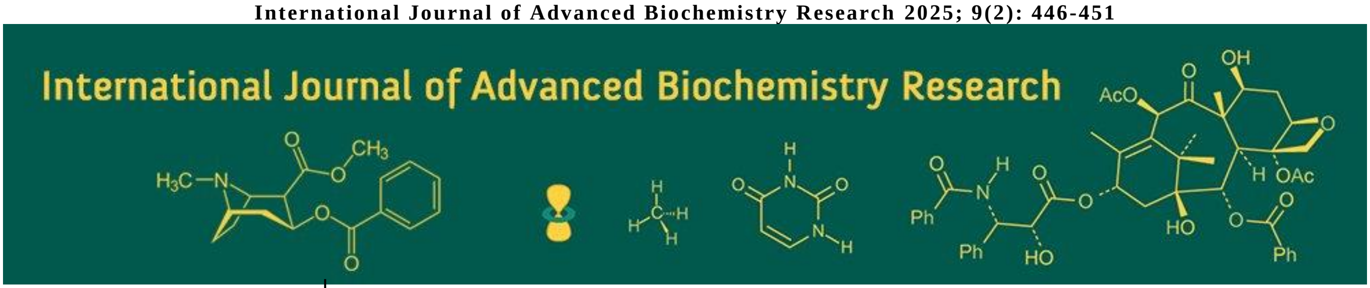

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Harnessing nature: Black soldier fly for sustainable organic waste management

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Abstract
The Black Soldier Fly (BSF), *Hermetia illucens*, is an efficient, sustainable method for converting organic waste into valuable biomass, such as animal feed, biodiesel, and chitin. This seminar explores BSF larvae's ability to reduce organic waste volume by up to 80%, mitigating environmental impacts like landfill use and transportation costs (Rindhe *et al*., 2019). BSF larvae process various organic materials, including food waste, manure, and agricultural byproducts, and biodegrade waste faster than methods like vermicomposting (Gold *et al*., 2018). They also control odors, bacterial growth, and pathogens, offering biosecurity benefits, particularly in livestock farming (Rindhe *et al*., 2019). With around 35% protein and 30% fat, BSF larvae serve as a sustainable alternative to traditional animal feed (Rindhe *et al*., 2019). Additionally, the larvae produce nutrient-rich residues for soil enrichment. The seminar also covers the infrastructure and facilities required for large-scale BSF rearing, such as waste receiving units, BSF rearing units, and post-treatment processes. BSF offers a solution to food insecurity, resource scarcity, and environmental degradation, particularly in low-and middle-income regions. The seminar concludes by emphasizing BSF's broader environmental and economic benefits.

Keywords: Black soldier fly, waste management, insect protein

Introduction

H. illucens is believed to have originated in the savannahs of South America and is commonly found in tropical, subtropical, and temperate climates (M.T. James, 1935) [11]. Its geographic distribution remains an intriguing topic, as evidenced by the discovery of an *H. illucens* larva in Isabella d'Aragona's coffin (G. Benelli, 2014) [1]. Despite controlling housefly populations, *H. illucens* does not pose a threat to human health, the environment, or crops. The larvae are saprophytic insects that consume organic waste, such as plant and animal carcasses, as well as waste from homes, businesses, and farms. As the larvae decompose organic matter, they can break down harmful bacteria like Salmonella spp. and Escherichia coli, reducing the environmental impact of such waste (Erickson, 2004) [8]. Due to its ability to convert organic waste into valuable organic matter—including proteins, lipids, amino acids, peptides, chitin, and vitamins—*H. illucens* has been recognized as a beneficial and non-pest insect. Its broad nutritional range makes it a promising source of protein, with a digestibility rate higher than that of vegetable proteins, and comparable to fish and meat proteins (Liu *et al*., 2019) [13]. Research into replacing conventional animal feed with *H. illucens* protein has made significant progress (Cumins, 2017) [5]. Moreover, chitin isolated from its puparium can be used to produce chitosan, a valuable compound with various applications (Wasko, 2016) [26]. *H. illucens* also produces antimicrobial peptides that have activity against several bacterial species (Wasko, 2016) [26]. Additionally, the insect's grease holds potential for producing high-tech products such as biodiesel. Given its high nutritional value and versatility, *H. illucens* presents considerable opportunities for exploitation in various industries. However, challenges remain in scaling up breeding and processing methods to meet industrial needs, and more research is needed to optimize the extraction of its valuable components for high-value products (Bondari *et al*., 1987; Sheppard & Tomberlin, 2002) [2, 21].

Biological morphology of black soldier fly (*Hermetia illucens*)

The black soldier fly (*H. illucens*) is an insect belonging to the family Stratiomyidae, widely recognized for its remarkable adaptability and ecological significance. Originally native to tropical and subtropical regions, it has spread globally and is now found in various environments. The adult flies are characterized by their distinctive black or dark brown coloration and a unique morphology that sets them apart from other flies.

Its life cycle includes four distinct stages: egg, larva, pupa, and adult. The larval stage is especially important due to its voracious appetite for organic waste, including food scraps, animal manure, and other biodegradable materials. This capability positions the black soldier fly as a vital player in waste management and nutrient recycling, offering a sustainable solution to the growing global challenge of organic waste disposal.

In addition to its environmental benefits, the larvae are a rich source of protein and fat, making them an excellent ingredient for animal feed, particularly in aquaculture and poultry industries. As research into the black soldier fly continues to expand, its potential for contributing to sustainable agriculture, food security, and waste reduction becomes increasingly recognized. This introduction highlights the importance of the black soldier fly as both an ecological resource and an innovative solution to modern agricultural challenges.

1. General Anatomy

The black soldier fly has a distinct morphology, measuring 10-20 mm in length with a black or dark brown, elongated body divided into three segments: head, thorax, and abdomen.

- **Head:** Equipped with compound eyes for wide vision, short club-shaped antennae, and non-feeding mouthparts used mainly for mating.
- **Thorax:** Consists of three segments, each with a pair of legs. It has reduced forewings transformed into halteres for balance during flight.
- **Abdomen:** Elongated and segmented, housing reproductive and digestive organs. Females have an ovipositor for egg-laying.
- **Wings:** Two larger functional wings that help with flight and dispersal for mating and habitat searching.
- **Legs:** Robust legs designed for walking, perching, and gripping surfaces, essential for mating and resting.
- **Coloration:** Predominantly black or dark brown, providing camouflage against predators.

2. Life Cycle Morphology

The black soldier fly undergoes a complete metamorphosis, consisting of four life stages: egg, larva, pupa, and adult. Each stage is characterized by specific morphological adaptations.

- **Eggs:** Females lay 500-900 small, white, elongated eggs in clusters within organic matter, providing optimal hatching conditions.
- **Larvae:** Larvae, growing up to 25 mm, have a cylindrical body with a dark exoskeleton and powerful mandibles, allowing efficient waste breakdown.
- **Pupae:** Larvae transform into pupae, which are darker and more rigid, offering protection during this vulnerable stage. Pupae are found in soil or organic substrates.
- **Adults:** Adults have well-developed wings, with males being smaller than females. Males often exhibit territorial behaviors.

3. Physiological Adaptations:

3. Physiological Adaptations: The morphology of the black soldier fly is closely linked to its physiological adaptations, which enable it to thrive in diverse environments.

- **Digestive System:** The larvae have a highly efficient digestive system adapted to breaking down organic materials. Their gut is equipped with microbial communities that assist in the fermentation and digestion of complex substrates, enhancing nutrient absorption.
- **Respiration:** Black soldier fly larvae breathe through spiracles located along the sides of their bodies, allowing for gas exchange even when buried in organic matter. This adaptation is crucial for their survival in oxygen-depleted environments.
- **Thermoregulation:** The ability of larvae to thrive in various temperatures, from 20 °C to 40 °C, reflects their adaptability. Their morphology aids in heat regulation, allowing them to maintain activity levels across different thermal conditions.

4. Ecological Characteristics

- **Lifecycle:** BSF has a rapid lifecycle, with larvae hatching from eggs and consuming organic waste like food scraps and manure.
- **Habitat:** They thrive in warm, humid environments, often found in composting sites and decaying organic matter.
- **Feeding Behavior:** BSF larvae are detritivores, feeding on decomposing organic material, particularly preferring high-protein, nutrient-rich substrates for better growth.
- **Nutritional Efficiency:** They efficiently convert waste into valuable products like protein and fat, contributing to nutrient recycling in ecosystems.

5. Environmental Stressors

- **Temperature and Humidity:** BSF larvae thrive at 25-30 °C (77-86°F). Extreme temperatures (<15 °C or >40 °C) hinder development.
- **pH Levels:** BSF larvae prefer slightly acidic to neutral pH (6.0-7.0). Extreme pH levels can harm their growth.
- **Nutrient Availability:** A lack of key nutrients (e.g., nitrogen and phosphorus) in the substrate can slow larval growth.
- **Contaminants:** Environmental contaminants like heavy metals, pesticides, and pathogens can negatively affect larval health and waste processing efficiency.
- **Microbial Interactions:** Beneficial microbes enhance nutrient availability, while pathogenic ones can harm larvae development.

Application of black soldier fly in waste management

Rearing *H. illucens* has been suggested as an effective method of disposing organic waste by turning them into a protein and fat-rich biomass fit for a variety of uses, such as animal feed for all livestock species, biodiesel, and chitin production (Van Huis *et al.*, 2013; Diener *et al.*, 2011) [25, 6].

In western nations, they have been employed to lessen animal excrement in commercial swine and poultry farms; however, this technique is uncommon in India. About 58% of the dry matter in an organic source can be converted by black soldier fly larvae into premium animal feed (Sheppard *et al.*, 1994) [3]. Around 1.3 billion tonnes of food are lost annually from the world's food production, making it a fantastic chance to use these flies for bioconversion (Gustavsson *et al.*, 2011) [10].

Compared to worms employed in vermicomposting, the larvae of black soldier fly can break down organic waste material more quickly. Approximately one kilogram of household food waste can be consumed daily by a colony of 2,000 larvae (Rindhe *et al.*, 2019) [20]. Because of their big, strong chewing mouthparts, they can quickly get rid of odor by consuming organic substances before they have a chance to break down. Furthermore, the larvae alter the manure's microbiota, which may lessen dangerous bacteria like *Salmonella enterica* and *Escherichia coli* 0157:H7 (Van Huis *et al.*, 2013) [25]. According to reports, the larvae contain natural antibiotics that influence the animal feed's growth stimulator (Newton *et al.*, 2007) [23]. Apart from the larvae, soil amendments can be made from the leftovers or castings that are produced during controlled larval rearing.

The prepupa which is the final stage of larvae, moves away from the food source in pursuit of a safe and dry location for pupation. The adult emerges from the pupation that takes place inside the larval skin after around 14 days. The adults have a poor flight and are sluggish.

The females mate two days after emerging and deposit their eggs in crevices and cracks next to a food source. Eggs are never placed directly onto the damp, decomposing substrate because of the comparatively long time (3–4 days) between oviposition and eclosion. The adult of *H. illucens* just uses its body fat reserve and does not feed.

As a result, the fly cannot be considered unhygienic or a disease vector because it does not come into contact with any fresh or decomposing organic material, including food. Larvae begin feeding on the garbage after hatching, resulting in about 55% reduction in dry mass volume waste (Myers *et al.*, 2008; Newton *et al.*, 1977; Sheppard, 1987) [14, 17, 2]. Fresh material is processed very quickly. Bacterial development is controlled or limited due to high larval densities and the larvae's ravenous hunger, which minimizes the formation of unpleasant odors.

An additional advantage of *H. illucens* is its capacity to repel oviposition of female house flies (Bradley and Sheppard, 1984) [3], a serious disease vector especially in developing countries, where open defecation and inappropriate sanitation account for dangerous sources of pathogens. Larvae can reach maturity in as little as two weeks when there are enough of food sources, such as garbage deposits. Low temperatures and a lack of food, however, can prolong the larval stage by up to four months. Their remarkable life cycle flexibility can be highly useful for both storing larvae to incubate a new population and regulating populations during times of garbage shortage.

The prepupae, exhibits a noticeable migration pattern. For them to effectively pupate into adult flies, they must quit the feeding source. The prepupae have reached their maximum size at this point and they contain high amounts of protein (36–48%) and fat (31–33%) to support their metamorphosis (Hale, 1977; St-Hilaire *et al.*, 2007; Stamer, 2004) [17, 23, 22]. Comparing this last instar to the feeding larva, there are minor morphological differences. For instance, its labrum is hunched over like an eagle's beak. They are drawn to an appropriate pupation site using it as a hook. Larvae emerge from a rimmed container and ascend a ramp (30–45°) before arriving at a collecting jar fastened to the ramp's end. Waste managers find this method very appealing because of the production of these energy-rich prepupae.

Salient features of black soldier fly

The larvae are composed of approximately 35% protein and 30% crude fat. This high-quality insect protein is a valuable feed source for fish and chicken breeders. It is a good substitute for fish meal, according to feed experiments. It has been demonstrated that feeding garbage to larvae inactivates bacteria that spread disease, including *Salmonella* spp. This suggests that applying this technique at the farm level or when handling waste of animal origin (such as chicken manure or butcher waste) generally lowers the likelihood of disease transmission between animals and between animals and humans. Nevertheless, material reduction (±80%) rather than pathogen inactivation is the primary method used to reduce risk.

On a wet weight basis, waste reduction of up to 80% has been shown. Thus, the expenses associated with waste transportation and the amount of area needed for landfills can be significantly decreased if treatment is implemented at the point of bio-waste formation. Additionally, treating organic waste could lessen open dumping, which is still a regrettable reality in areas with low and middle incomes.

The residue, which is comparable to compost, is rich in organic matter and nutrients and, when applied to farmland, aids in halting soil erosion.

It is appropriate for low-income populations without skilled laborers because it doesn't require complex, expensive equipment to function.

Biodiesel production from black soldier fly

The Black Soldier Fly Larvae (BSFL) is cultivated for 14 days using food waste as feed with approximately 25,000 larvae grown per square meter, yielding around 5 kg of larvae per square meter. After harvesting, the BSFL is dried at 60 °C in a conveyor oven. Lipid is then extracted from the dried larvae using hexane following a liquid-liquid extraction method. The lipid is separated from solids through centrifugation and various biochemical components (protein, lipid, carbohydrate, ash, and moisture contents) were analyzed according to AOAC methods.

For biodiesel synthesis, 5 g of extracted BSFL lipid undergoes transesterification with methanol under varying conditions of lipid-to-methanol ratio, catalyst amount (H_2SO_4), reaction temperature and time. The biodiesel is purified through distillation and decantation to remove methanol and glycerol, respectively. The crude biodiesel is washed with distilled water and its weight is measured. The total fatty acid methyl ester (FAME) content was determined using chromatography.

Antimicrobial biomass from lactic acid fermentation by black soldier fly

1. Collection of Insect Waste

Prepupae of black soldier fly were collected and placed in dry, ventilated polyethylene containers to allow fly emergence.

2. Bacterial Strains

Two bacterial strains is used in fermentation experiments: *Lacticaseibacillus rhamnosus* 1473, isolated from Parmigiano Reggiano cheese and *Lactiplantibacillus plantarum* 285, isolated from Brazilian cheese. The antimicrobial activity of the insect waste is tested against three pathogenic strains: *Salmonella enteric*, *Listeria monocytogenes* and *Escherichia coli*. Lactic acid bacteria (LAB) strains are stored at −80 °C in De Man, Rogosa and Sharpe (MRS) broth containing 12.5% glycerol. The pathogenic strains were also maintained at −80 °C in tryptic soy broth (TSB) with 12.5% glycerol.

3. Fermentation

To prepare the substrates for fermentation, puparia and adults are crushed into small particles using a laboratory grinder. Water (70% v/w) and sugar (8.5% w/w) were then added, and the mixture was sterilized by autoclaving at 121 °C for 20 minutes in a glass jar. Similarly, prepupae were ground into small particles, combined with sugar (8.5% w/w) and sterilized under the same conditions. Before fermentation, the LAB strains were revived by transferring them twice to MRS broth (3% v/v) and incubating them for 24 hours: *L. plantarum* 285 at 30 °C and *L. rhamnosus* 1473 at 37 °C. Each strain is then inoculated into MRS broth (3% v/v) and incubated for 15 hours at their respective temperatures. The bacterial cultures are centrifuged (12,857× g, 10 minutes, 4 °C), washed twice in Ringer solution (VWR, UK) and suspended in sterile distilled water. Next, 30 grams of puparia, adults, and prepupae are inoculated with the bacterial suspension. The inoculated substrates are incubated for 72 hours: *L. plantarum* 285 at 30 °C and *L. rhamnosus* 1473 at 37 °C.

Equipments required

1. **Love Cage:** Strong mosquito netting with a central tunnel hole, zipper opening, and corner loops. Fits 6,000-10,000 flies. One hanger per cage.
2. **Attractants:** Two per love cage.
3. **Pedestals and Shading Basket:** Four small pedestals and one larger basket, bigger than attractant container.
4. **Water Basin:** One per love cage, with slits in the lid for cotton cloth.
5. **Cotton Towel:** One per love cage.
6. **Egg Media Units**: Ten per love cage.
7. **Movable Frame with Light:** Serves multiple love cages.
8. **Stick:** Two-meter stick with hook.
9. **Ant Traps:** Four per love cage, with water inside.
10. **Cage Table:** Holds up to three love cages, frame high enough for cages to rest.
11. **Binder Clips:** Eight for pedestals and connecting transfer tunnel.

Optimal environmental conditions and food sources required for rearing black soldier fly

1. **Warm climate:** A temperature of 24 to 30 °C is excellent. The larvae will crawl away from the food in search of a cooler spot if it gets too hot. The larvae will consume less, develop more slowly and slow down their metabolism if it is too cold.
2. **Shaded environment:** Larvae are light-averse and will always look for an area that is shady and out of direct sunshine. They will go deeper into the food layer to avoid the light if their food supply is exposed to it.
3. **Water content of the food:** For the larvae to consume the material, the food source must be somewhat moist, with a water content of 60% to 90%.
4. **Nutrient requirements of the food:** Good larval growth is the outcome of substrates high in readily available carbs and protein. According to ongoing study, garbage that has already undergone bacterial or fungal breakdown may be easier for the larvae to eat.
5. **Particle size of the food:** The larvae can more easily obtain nutrients if the substrate is provided in minute pieces, or even in a liquid form because they lack chewing mouthparts.

Steps in Production of black soldier fly

1. **Step 1:** Hang the clean love cage using loops.
2. **Step 2:** Weigh the love cage and hanger together.
3. **Step 3:** Attach the hanger to the mobile frame using a long stick.
4. **Step 4:** Connect the two cage tunnels with binder clips, move the frame to the first dark cage, turn on the light, and gently shake to release flies.
5. **Step 5:** Weigh the love cage, then move it to the next dark cage after 30 minutes. Repeat for all dark cages.
6. **Step 6:** Turn off the light, disconnect the cage from the final dark cage, and seal the tunnels with rope.
7. **Step 7:** Weigh the love cage again, and calculate the number of flies based on weight and average fly weight.
8. **Step 8:** Move the love cage to the table using the hook and hanger.
9. **Step 9:** Prepare attractant: mix 100g dead flies, 200g nursery residue, 200g old attractant, and 1L fruit fermenting water.
10. **Step 10:** Create 10 egg bundles with wooden sheets and pushpins, holding them together with rubber bands.
11. **Step 11:** Prepare a water bowl with a cotton cloth submerged in water.
12. **Step 12:** Open the love cage, insert the attractant, cover with egg bundles, place the shade basket upside down, and close the cage. Set the water bowl on the basket.
13. **Step 13:** Label the love cage with the date and place it on the table.

Challenges

1. **Temperature Sensitivity:** BSF larvae need a specific temperature range (27-35 °C), making climate control essential in some areas.
2. **Waste Composition:** Some materials (e.g., high salt or toxic substances) can harm the larvae, complicating feedstock selection.
3. **Scaling Up:** Expanding BSF systems requires costly infrastructure, which can be a barrier.
4. **Regulatory Issues:** Compliance with health and safety standards can be complex, depending on local regulations.
5. **Public Perception:** Overcoming stigma about using insects for waste processing and feed is a challenge.
6. **Waste Residue Management:** Managing leftover frass and unprocessed material requires additional solutions.
7. **Competition and Market Demand:** Growing demand for insect protein may create competition for resources and market share.

8. **Life Cycle Management:** Managing the BSF life cycle is complex, with challenges in breeding and preventing overcrowding or disease.
9. **Nutritional Balance:** Ensuring larvae receive a balanced diet for optimal growth can be difficult with varying waste inputs.

Conclusion

- BSF larvae offer a sustainable solution for organic waste management, reducing pollution and producing valuable by-products. They can decrease waste volume by up to 80% and help reduce pathogens like Salmonella and E. coli, making them ideal for farm-level waste disposal.
- The larvae are rich in protein and fat, providing a sustainable alternative to traditional animal feed, particularly in regions with limited resources. Their simple rearing process requires minimal infrastructure, making it accessible to low-income populations.
- BSF's ability to adapt to various environmental conditions and waste types allows it to be integrated globally. It helps reduce landfill waste, prevents open dumping, and improves soil health through nutrient-rich residue.
- Overall, BSF larvae play a crucial role in reducing food waste, enhancing agricultural productivity, and minimizing environmental impacts. As technology advances, BSF rearing could become a key part of sustainable waste management and circular economies worldwide.

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