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Black soldier fly (Hermetia illucens): A natural Bio-recycling engineer and potential bioindicator of organic waste in central India

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Abstract
The increasing generation of organic waste due to rapid urbanization and population growth has emerged as a major environmental challenge worldwide, necessitating the development of sustainable and economically viable waste management strategies. Among various biological approaches, the Black Soldier Fly (*Hermetia illucens* Linnaeus, 1758) has gained global recognition as an efficient bioconversion agent capable of transforming organic waste into valuable biological resources. This review critically examines the ecological significance, waste conversion efficiency, environmental benefits, and emerging applications of *H. illucens*, with particular emphasis on its potential role as a bioindicator of organic waste accumulation in Central India. Available studies indicate that Black Soldier Fly larvae (BSFL) can efficiently process a wide range of organic substrates, including household food waste, fruit residues, agricultural by-products, and livestock manure, resulting in waste reduction rates ranging from 50–80%. Simultaneously, BSFL generate high-value products such as protein-rich biomass, lipid-rich feedstock, and nutrient-rich frass, thereby supporting the principles of circular bioeconomy and waste-to-wealth systems. In addition, BSFL-based waste treatment systems have been reported to reduce landfill dependency, nutrient loss, and greenhouse gas emissions compared to conventional waste disposal practices. Recent research has primarily focused on the utilization of BSFL for sustainable animal feed production, aquaculture, poultry nutrition, biodiesel generation, and organic fertilizer development. However, despite extensive investigations into its waste valorization potential, the ecological significance of *H. illucens* as a biological indicator of organic waste accumulation remains largely unexplored. The natural colonization of household organic waste by BSF populations observed in Central India suggests a strong ecological association between species abundance and organic waste availability, highlighting its potential application as a cost-effective bioindicator for monitoring waste accumulation, decomposition dynamics, and urban ecosystem health.
This review identifies critical knowledge gaps related to population ecology, seasonal abundance patterns, substrate preference, microbiome interactions, and bioindicator applications of *H. illucens* under tropical Indian conditions. The synthesis of available evidence suggests that Black Soldier Fly represents a unique interface between environmental sustainability, resource recovery, climate change mitigation, and ecosystem monitoring. Further investigations integrating ecological assessment and waste management applications may establish *H. illucens* as both a natural bio-recycling engineer and a reliable bioindicator species, thereby contributing to sustainable waste management frameworks and circular bioeconomy initiatives in India and other developing regions.

Keywords: *Hermetia illucens*, black soldier fly, organic waste management, waste-to-wealth, circular bioeconomy, bioindicator, resource recovery, sustainable development, central India.

Introduction

The rapid increase in human population, urbanization, and changing consumption patterns has resulted in a significant rise in organic waste generation worldwide. According to recent estimates, biodegradable organic waste constitutes a major fraction of municipal solid waste and poses serious environmental, economic, and public health challenges when improperly managed (Amrul *et al*., 2022) [1]. Conventional waste disposal methods such as landfilling, open dumping, and incineration are often associated with greenhouse gas emissions, nutrient losses, groundwater contamination, and ecosystem degradation (Parodi *et al*., 2021) [15]. Consequently, the development of sustainable and environmentally friendly waste management strategies has become a global priority. Among the emerging biological solutions, the Black Soldier Fly (*Hermetia illucens* Linnaeus, 1758) has attracted considerable scientific attention because of its exceptional capacity to convert diverse organic wastes into valuable biological products (Wang & Shelomi, 2017) [20]. Native to the Americas but now distributed throughout tropical and subtropical regions worldwide, *H. illucens* belongs to the family Stratiomyidae and is recognized as one of the most efficient organic waste bioconverters known to science (Diener *et al*., 2011) [5]. The larval stage of this species is particularly important due to its voracious feeding behavior and ability to rapidly process large quantities of decomposing organic matter. Recent studies have demonstrated that Black Soldier Fly larvae (BSFL) can reduce organic waste volume by approximately 50–80% while simultaneously producing protein-rich biomass, lipid-rich feedstock, and nutrient-enriched frass suitable for agricultural applications (Amrul *et al*., 2022; Siddiqui *et al*., 2022) [1, 17]. Unlike many other synanthropic flies, adult BSF are not considered significant vectors of human diseases because they possess reduced feeding activity and rarely interact with human food sources (Wang & Shelomi, 2017) [20]. This characteristic makes the species particularly attractive for large-scale waste management and resource recovery programs.

Beyond waste reduction, BSFL have emerged as an important component of the circular bioeconomy. Their biomass is increasingly utilized in aquaculture, poultry production, livestock nutrition, biodiesel production, and bioproduct development (Lu *et al*., 2022; Surendra *et al*., 2020) [18]. The ability of BSF to transform low-value organic waste into high-value biological products has led many researchers to describe the species as a "natural bio-recycling engineer" and a cornerstone organism in waste-to-wealth systems (Parodi *et al*., 2021) [15].

Furthermore, BSF-based waste treatment systems have been reported to reduce environmental impacts associated with traditional waste disposal methods. Several life-cycle assessment studies indicate lower greenhouse gas emissions, reduced landfill dependence, and improved nutrient recycling compared with conventional organic waste treatment systems (Mertenat *et al*., 2019; Sarpong *et al*., 2019) [14, 16]. Such findings highlight the growing importance of BSF in climate-smart waste management and sustainable development initiatives. Despite substantial advances in waste bioconversion research, relatively little attention has been given to the ecological significance of *H. illucens* as a potential bioindicator species. The natural occurrence and abundance of BSF populations are closely associated with organic waste availability, substrate quality, moisture content, and decomposition dynamics. Consequently, the species may provide valuable ecological information regarding organic waste accumulation and ecosystem health. This potential bioindicator role remains largely unexplored, particularly in tropical developing countries where biological monitoring tools are often limited. In Central India, increasing urbanization and changing waste generation patterns have created favorable habitats for BSF colonization.

Observations of naturally occurring BSF populations in household organic waste systems suggest that the species may already be performing important ecosystem services at the local level. Understanding the ecological relationship between BSF abundance and organic waste availability could provide a novel framework for integrating waste management, environmental monitoring, and biodiversity conservation.

Therefore, the present review aims to synthesize current knowledge on the biology, ecology, waste conversion efficiency, environmental benefits, and waste-to-wealth applications of *Hermetia illucens*. Special emphasis is placed on evaluating its potential role as a bioindicator of organic waste accumulation, identifying existing knowledge gaps, and highlighting future research priorities relevant to Central India and other developing regions.

Biology and ecological significance of *Hermetia illucens*

The Black Soldier Fly (**Figure 01**) (*Hermetia illucens* Linnaeus, 1758) is a member of the family Stratiomyidae and is widely recognized as one of the most ecologically significant insects associated with the decomposition of organic matter. Originally considered native to the Neotropical region, the species is now distributed across tropical, subtropical, and many temperate regions of the world due to its remarkable ecological adaptability and association with human-generated organic waste (Marshall *et al*., 2015; Wang & Shelomi, 2017) [12, 20]. In recent years, *H. illucens* has gained considerable scientific attention because of its role in waste bioconversion, nutrient recycling, and sustainable resource recovery.

Fig 1: Mature larval stage of Black Soldier Fly (*Hermetia illucens*), the principal waste-degrading stage responsible for organic waste conversion.

The species undergoes complete metamorphosis consisting of egg, larval, prepupal, pupal, and adult stages. Under favorable environmental conditions, its life cycle is completed within approximately 35–60 days, depending on temperature, humidity, and food availability (Tomberlin *et al*., 2009) [19]. Female adults typically lay 400–800 eggs near decomposing organic substrates. After hatching, the larvae actively feed on organic matter and rapidly accumulate biomass rich in proteins and lipids. Among all developmental stages, the larval phase is considered the most ecologically and economically important because it is responsible for the decomposition and conversion of organic waste into valuable biological products (Diener *et al*., 2011; Holmes *et al*., 2013) [5, 7].

One of the most remarkable characteristics of *H. illucens* is its ability to exploit a wide range of organic substrates. The larvae successfully develop on household food waste, fruit residues, vegetable waste, agricultural by-products, livestock manure, and other biodegradable materials (Surendra *et al*., 2020) [18]. Studies have shown that fruit-rich substrates, particularly banana, papaya, mango, and other soft fruit wastes, support rapid larval growth and higher biomass production compared with more fibrous organic materials (Gold *et al*., 2018) [6]. This exceptional feeding capacity allows the species to function as a highly efficient biological decomposer within both natural and human-modified ecosystems.

Unlike the common housefly (*Musca domestica*), adult Black Soldier Flies are not considered important vectors of human diseases. Adults possess reduced mouthparts and exhibit limited feeding behavior, reducing their interaction with human food and pathogenic microorganisms (Wang & Shelomi, 2017) [20]. This ecological distinction makes the species particularly suitable for large-scale waste management systems and contributes to its growing acceptance as a beneficial insect. Because of its ability to transform organic waste into useful biological products while posing minimal public health risks, *H. illucens* is increasingly regarded as an environmentally friendly alternative to conventional waste treatment methods.

The ecological importance of Black Soldier Fly extends beyond waste reduction. During feeding, larvae accelerate the decomposition process and facilitate the recycling of essential nutrients such as carbon, nitrogen, and phosphorus. Research indicates that BSF larvae can reduce organic waste volume by approximately 50–80%, depending on substrate composition and environmental conditions (Amrul *et al*., 2022) [1]. Simultaneously, nutrients present in waste materials are converted into larval biomass and nutrient-rich frass, which can be utilized as an organic fertilizer in agricultural systems (Beesigamukama *et al*., 2020) [2]. Through these processes, *H. illucens* contributes significantly to nutrient cycling and ecosystem functioning.

Recent studies have also highlighted the importance of microbial interactions in BSF ecology. The larval gut contains diverse microbial communities that assist in the breakdown of complex organic compounds and improve nutrient assimilation efficiency (Klammsteiner *et al*., 2020) [8]. Furthermore, BSF larvae have been reported to suppress certain pathogenic microorganisms through competition and antimicrobial activity, thereby improving substrate sanitation and enhancing the efficiency of organic waste conversion systems (Bruno *et al*., 2019) [3]. These interactions further strengthen the ecological role of the species within decomposer communities. Because of its profound influence on decomposition dynamics, nutrient turnover, microbial communities, and resource availability, *H. illucens* may be considered a biological ecosystem engineer. Its activities directly modify environmental conditions and facilitate the transformation of organic waste into valuable ecological resources. Consequently, many researchers now describe the species as a natural "bio-recycling engineer" and an important component of circular bioeconomy systems (Parodi *et al*., 2021) [15]. Beyond its established role in waste bioconversion, the species may also possess considerable potential as a bioindicator of organic waste accumulation. The occurrence and abundance of BSF populations are strongly associated with the availability of decomposing organic matter, moisture levels, and substrate quality. Observations of naturally colonized household organic waste in Central India suggest that the presence of *H. illucens* may reflect local patterns of organic waste generation and decomposition. Such characteristics indicate that the species could serve as a cost-effective biological indicator for monitoring organic waste accumulation, ecosystem health, and environmental quality. Although this aspect remains largely unexplored, future investigations focusing on population dynamics and habitat associations may establish *H. illucens* as an important bioindicator species in tropical urban ecosystems.

Black soldier fly as a natural bio-recycling engineer

The Black Soldier Fly (*Hermetia illucens*) has emerged as one of the most efficient biological agents for organic waste recycling and resource recovery. Due to its remarkable ability to convert a wide variety of biodegradable wastes into valuable biomass, the species is increasingly recognized as a natural “Bio-Recycling Engineer” within circular bioeconomy systems (Parodi *et al*., 2021) [15]. Unlike conventional waste treatment methods, which often require significant energy inputs and generate environmental pollutants, Black Soldier Fly larvae (BSFL) utilize naturally occurring biological processes to transform organic waste into useful products with minimal environmental impact (Amrul *et al*., 2022) [1]. One of the most significant characteristics of BSFL is their extraordinary feeding capacity. The larvae can efficiently consume and process large quantities of household food waste, fruit residues, vegetable waste, agricultural by-products, animal manure, and other biodegradable materials (Diener *et al*., 2011) [5]. Several studies have demonstrated that BSFL can reduce organic waste volumes by approximately 50–80%, depending on substrate composition and environmental conditions (Amrul *et al*., 2022; Siddiqui *et al*., 2022) [1, 17]. This rapid bioconversion not only minimizes waste accumulation but also accelerates nutrient recycling within ecosystems. The waste conversion process carried out by BSFL represents a highly efficient example of the “Waste-to-Wealth” concept. During feeding, larvae assimilate nutrients from decomposing organic matter and convert them into protein-rich and lipid-rich biomass. Simultaneously, the residual material, commonly known as frass, remains enriched with essential nutrients and organic matter that can be utilized as an organic fertilizer (Beesigamukama *et al*., 2020) [2]. Consequently, a single biological process generates multiple value-added products, including insect biomass, animal feed ingredients, organic fertilizers, and bioenergy feedstocks. Research has shown that BSFL possess exceptional efficiency in converting low-value organic substrates into high-quality biological resources. The larval biomass contains substantial levels of crude protein, essential amino acids, beneficial fatty acids, and micronutrients, making it a promising alternative feed source for aquaculture, poultry, and livestock production (Wang & Shelomi, 2017 [20]; Lu *et al*., 2022). As global demand for sustainable protein sources continues to increase, BSF-based production systems are being explored as environmentally sustainable alternatives to conventional feed ingredients such as fishmeal and soybean meal. The environmental benefits of BSF-mediated bioconversion extend beyond waste reduction and resource recovery. Organic waste disposed in landfills undergoes anaerobic decomposition, resulting in the release of methane and other greenhouse gases that contribute significantly to climate change. In contrast, BSFL-based waste treatment systems divert organic waste from landfills and facilitate rapid aerobic decomposition, thereby reducing greenhouse gas emissions and improving waste management efficiency (Mertenat *et al*., 2019; Sarpong *et al*., 2019) [14, 16]. Life-cycle assessments have further suggested that BSF systems exhibit lower environmental footprints compared with many traditional waste treatment approaches.

Recent studies have also highlighted the species' role in improving sanitation and environmental health. Active larval feeding suppresses the proliferation of undesirable microorganisms and reduces odors associated with decomposing waste (Bruno *et al*., 2019) [3]. Furthermore, the rapid consumption of organic substrates often limits the breeding opportunities available to pestiferous flies and other nuisance insects, thereby contributing to improved environmental hygiene. The growing recognition of Black Soldier Fly as a natural bio-recycling engineer is closely linked to its ability to integrate waste management, nutrient recovery, sustainable agriculture, and climate change mitigation within a single biological framework. By converting organic waste into valuable products while simultaneously reducing environmental pollution, *Hermetia illucens* represents one of the most promising insect species for achieving circular bioeconomy objectives and sustainable development goals (Parodi *et al*., 2021) [15]. Its increasing adoption in waste management systems worldwide demonstrates the potential of insect-based technologies to address some of the most pressing environmental challenges of the twenty-first century.

BSF and the waste-to-wealth concept

The concept of "Waste-to-Wealth" has emerged as a key component of the circular bioeconomy, emphasizing the transformation of waste materials into valuable products and resources. In recent years, the Black Soldier Fly (*Hermetia illucens*) has gained global recognition as one of the most promising biological agents capable of converting organic waste into economically valuable products while simultaneously reducing environmental pollution (Parodi *et al*., 2021) [15]. Owing to its remarkable feeding capacity and rapid growth, the species represents a sustainable solution for addressing the growing challenges of organic waste accumulation and resource scarcity.

Black Soldier Fly larvae (BSFL) possess the unique ability to utilize a wide variety of biodegradable materials, including household food waste, fruit and vegetable residues, agricultural by-products, animal manure, and market waste, as feeding substrates (Diener *et al*., 2011) [5]. During the feeding process, larvae efficiently convert these low-value waste materials into nutrient-rich biomass, thereby transforming environmental liabilities into valuable biological resources. Studies have reported that BSFL can reduce organic waste volumes by 50–80%, significantly lowering the burden on conventional waste disposal systems while enhancing resource recovery (Amrul *et al*., 2022; Siddiqui *et al*., 2022) [1, 17].

One of the most economically important outputs of BSF bioconversion systems is the production of protein-rich larval biomass. The larvae contain substantial quantities of crude protein, essential amino acids, and beneficial fatty acids, making them a promising alternative ingredient for aquaculture, poultry, and livestock feeds (Wang & Shelomi, 2017 [20]; Lu *et al*., 2022). With increasing concerns regarding the sustainability of fishmeal and soybean meal production, BSF-derived protein is receiving considerable attention as an environmentally friendly and economically viable substitute. Several studies have demonstrated that insect-based feeds can partially replace conventional feed ingredients without adversely affecting animal growth performance or nutritional quality (Makkar *et al*., 2014) [10].

In addition to protein production, BSF larvae accumulate considerable quantities of lipids that can be utilized for biodiesel and other bioenergy applications. Research indicates that BSF-derived oils possess favorable physicochemical characteristics suitable for renewable fuel production, thereby contributing to sustainable energy generation and reducing dependence on fossil fuels (Surendra *et al*., 2020) [18]. This ability to simultaneously produce feed and energy resources further strengthens the species' role in waste-to-wealth frameworks.

Another significant product generated through BSF bioconversion is frass, the residual organic material produced after larval feeding. Frass is rich in organic matter and plant nutrients such as nitrogen, phosphorus, and potassium, making it a valuable organic fertilizer for sustainable agriculture (Beesigamukama *et al*., 2020) [2]. Recent studies have demonstrated that BSF frass can improve soil fertility, enhance microbial activity, and promote plant growth, thereby contributing to nutrient recycling and reducing the need for synthetic fertilizers (Klammsteiner *et al*., 2020) [8].

The environmental benefits associated with BSF-based waste valorization are equally significant. Conventional disposal of organic waste through landfilling often results in methane emissions, nutrient losses, and environmental contamination. In contrast, BSFL-based systems accelerate waste decomposition and facilitate resource recovery while reducing greenhouse gas emissions and landfill dependency (Mertenat *et al*., 2019) [14]. Life-cycle assessment studies have further revealed that BSF bioconversion systems generally exhibit lower environmental impacts than many traditional organic waste treatment technologies (Sarpong *et al*., 2019) [16].

Beyond economic and environmental advantages, the Waste-to-Wealth potential of BSF aligns closely with global sustainable development goals (SDGs), particularly those related to responsible consumption and production, climate action, food security, and sustainable cities (Parodi *et al*., 2021) [15]. The integration of BSF technology into municipal waste management systems, agricultural enterprises, and circular bioeconomy initiatives has the potential to create new employment opportunities while promoting sustainable resource utilization.

In developing countries such as India, where large quantities of biodegradable waste are generated daily, BSF-based technologies offer an innovative and low-cost approach for converting waste streams into valuable products. Observations of naturally occurring BSF populations in household organic waste systems in Central India suggest that the species is already performing important ecosystem services at the local level. Therefore, greater scientific attention toward the development and adoption of BSF-based waste valorization systems could significantly contribute to environmental sustainability, resource recovery, and rural bioeconomy development in the region.

Potential of bsf as a bioindicator of organic waste

Although the Black Soldier Fly (*Hermetia illucens*) has been extensively studied for its role in organic waste bioconversion and resource recovery, its potential as a bioindicator species remains comparatively underexplored. A bioindicator is an organism whose presence, abundance, behavior, or physiological condition reflects specific environmental conditions and can provide valuable information regarding ecosystem health and environmental quality (Markert *et al*., 2003) [11]. Owing to its strong ecological association with decomposing organic matter, *H. illucens* possesses several characteristics that support its potential use as a biological indicator of organic waste accumulation and decomposition dynamics. The occurrence and population density of Black Soldier Fly larvae are closely linked to the availability, composition, moisture content, and decomposition stage of organic substrates. Numerous studies have reported that BSF naturally colonizes environments rich in biodegradable organic matter, including food waste, fruit residues, animal manure, composting materials, and municipal organic waste streams (Diener *et al*., 2011; Gold *et al*., 2018) [5, 6]. Consequently, fluctuations in BSF abundance may provide indirect information regarding organic waste availability and the efficiency of decomposition processes within a given ecosystem. The species also demonstrates a high degree of sensitivity to environmental conditions such as temperature, humidity, substrate quality, and nutrient composition, all of which influence larval growth, survival, and reproductive success (Tomberlin *et al*., 2009) [19]. Because these environmental variables are often closely associated with waste accumulation patterns, BSF populations may serve as useful ecological indicators for monitoring the condition and management of organic waste ecosystems. Similar applications have been successfully demonstrated in other insect groups where species abundance and community composition have been utilized as indicators of habitat quality and environmental disturbance (McGeoch, 1998).

Recent observations from household organic waste systems in Central India further support this hypothesis. Natural colonization of kitchen waste by BSF populations indicates that the species responds rapidly to the availability of decomposing organic matter under local climatic conditions. The consistent occurrence of BSF larvae in fruit-rich and food-based waste substrates suggests a strong ecological relationship between species abundance and organic waste accumulation. Such observations provide preliminary evidence that BSF may function as a practical biological indicator of organic waste generation at household, community, and urban levels. From an environmental monitoring perspective, BSF offers several advantages as a potential bioindicator. The species is relatively easy to identify, has a well-defined life cycle, occurs naturally in waste-rich habitats, and exhibits measurable responses to changes in substrate quality and environmental conditions (Wang & Shelomi, 2017) [20]. Furthermore, because BSF populations are directly linked to biodegradable waste availability, monitoring their abundance may provide a cost-effective method for assessing waste management efficiency, decomposition activity, and nutrient recycling processes. The bioindicator potential of BSF may be particularly relevant in developing countries where rapid urbanization and inadequate waste management infrastructure contribute to increasing organic waste accumulation. In such regions, conventional environmental monitoring programs are often limited by financial and technical constraints. The use of naturally occurring organisms such as BSF could therefore offer an affordable and ecologically meaningful approach for evaluating waste-related environmental conditions and identifying areas requiring improved waste management interventions.

Despite these promising attributes, scientific investigations specifically examining BSF as a bioindicator species remain limited. Most existing research has focused on waste conversion efficiency, animal feed production, and circular bioeconomy applications, while ecological indicator functions have received comparatively little attention (Parodi *et al*., 2021) [15]. Future studies should therefore investigate the relationships between BSF population dynamics, waste composition, seasonal variation, environmental parameters, and ecosystem health indicators. Such research could establish standardized protocols for utilizing BSF as a biological monitoring tool in organic waste ecosystems. Given its ecological association with decomposing organic matter, sensitivity to environmental conditions, and widespread occurrence in waste-rich habitats, *Hermetia illucens* possesses significant potential as a bioindicator of organic waste accumulation and ecosystem functioning. Further research integrating population ecology, environmental monitoring, and waste management sciences may help establish Black Soldier Fly as both a natural bio-recycling engineer and a reliable ecological indicator species, particularly in rapidly urbanizing regions such as Central India.

Relevance to central India

Central India represents one of the rapidly developing regions of the country, where increasing urbanization, population growth, and changing consumption patterns have resulted in a substantial rise in organic waste generation. Cities and towns across Madhya Pradesh generate large quantities of biodegradable waste originating from households, vegetable markets, fruit markets, restaurants, educational institutions, and agricultural activities. A significant proportion of this waste remains inadequately managed, creating environmental challenges such as odor generation, greenhouse gas emissions, vector proliferation, and nutrient loss (CPCB, 2023). Consequently, sustainable and cost-effective biological approaches for organic waste management are becoming increasingly important for the region. The climatic conditions of Central India, characterized by warm temperatures, moderate to high humidity during the monsoon season, and abundant availability of organic substrates, provide favorable habitats for the establishment and development of Black Soldier Fly (*Hermetia illucens*) populations. Several studies have demonstrated that BSF larvae exhibit optimal growth and waste conversion efficiency under tropical and subtropical environmental conditions similar to those prevailing across much of Central India (Tomberlin *et al*., 2009; Gold *et al*., 2018) [6, 19]. These environmental characteristics make the region particularly suitable for the natural occurrence and potential utilization of BSF-based waste management systems. Observations from Jabalpur, Madhya Pradesh, revealed the natural colonization of household organic waste by BSF larvae, particularly in fruit-rich kitchen waste. The occurrence of the species under completely natural conditions suggests that local populations are already adapted to regional environmental conditions and may be contributing to organic matter decomposition and nutrient recycling at the household level. Such observations highlight the ecological significance of BSF within urban and peri-urban ecosystems and indicate the feasibility of utilizing naturally occurring populations for decentralized waste management practices.

From a waste management perspective, BSF-based bioconversion systems offer significant opportunities for Central India. Large quantities of fruit and vegetable waste generated from local markets, food processing units, and households could serve as suitable substrates for larval development and biomass production. The resulting protein-rich larval biomass and nutrient-rich frass could provide additional economic benefits while simultaneously reducing the environmental burden associated with organic waste disposal (Amrul *et al*., 2022; Beesigamukama *et al*., 2020) [1, 2]. Such integrated systems align closely with national initiatives promoting circular economy, sustainable agriculture, and resource recovery. The relevance of BSF extends beyond waste management alone. In regions where environmental monitoring infrastructure is limited, the natural occurrence and abundance of BSF populations may provide valuable information regarding organic waste accumulation and decomposition activity. Given the strong association between BSF and biodegradable waste, the species may serve as a practical ecological indicator for assessing waste generation patterns and environmental quality within urban ecosystems. This aspect is particularly relevant for rapidly expanding cities of Central India, where sustainable waste monitoring strategies are urgently needed.

Despite its considerable ecological and economic potential, research on *Hermetia illucens* in Central India remains limited. Most available studies originate from Europe, North America, Southeast Asia, and China, while region-specific information from the Indian subcontinent is still scarce. Consequently, investigations focusing on the distribution, seasonal dynamics, substrate preference, ecological interactions, and waste conversion efficiency of BSF under Central Indian conditions are essential. Such studies would not only improve scientific understanding of the species but also contribute to the development of locally adapted waste management and resource recovery strategies. The natural occurrence of BSF in household organic waste systems in Jabalpur provides preliminary evidence that the species may already be performing valuable ecosystem services within the region. Therefore, Central India offers a unique opportunity to explore the ecological, economic, and environmental significance of *Hermetia illucens* at both local and regional scales. Future research integrating entomology, waste management, urban ecology, and circular bioeconomy concepts may establish BSF as an important component of sustainable environmental management strategies in India.

Future research priorities

Despite the growing scientific interest in *Hermetia illucens*, several important aspects of its biology, ecology, and environmental applications remain insufficiently explored, particularly under Indian conditions. Future research should focus on generating region-specific data that can support the integration of Black Soldier Fly (BSF) into sustainable waste management and circular bioeconomy frameworks. One of the most promising research directions involves investigating the potential of BSF as a bioindicator of organic waste accumulation. While the species is widely recognized for its waste conversion efficiency, very limited information is available regarding the relationship between BSF population dynamics and environmental quality. Long-term monitoring studies examining species abundance, seasonal fluctuations, substrate preference, and waste accumulation patterns could establish BSF as a reliable ecological indicator for urban and peri-urban ecosystems (McGeoch, 1998; Markert *et al*., 2003) [11]. Another important research area concerns the population ecology and seasonal distribution of BSF in Central India. Information regarding its natural distribution, breeding periods, climatic preferences, and habitat associations remains scarce. Detailed ecological studies conducted across different seasons and habitat types could improve understanding of the species' adaptation to local environmental conditions and facilitate the development of region-specific waste management strategies.

Future investigations should also evaluate substrate-specific growth performance and waste conversion efficiency under Indian conditions. Comparative studies involving fruit waste, vegetable waste, market waste, agricultural residues, food-processing by-products, and livestock manure may help identify the most suitable substrates for maximizing larval productivity and resource recovery. Such information would be valuable for designing economically viable BSF production systems at both household and industrial scales (Diener *et al*., 2011; Amrul *et al*., 2022) [1, 5]. The interaction between BSF larvae and microbial communities represents another emerging field of research. Recent studies suggest that gut-associated microorganisms play a crucial role in organic matter degradation, nutrient assimilation, and pathogen suppression (Klammsteiner *et al*., 2020) [8]. Advanced metagenomic and microbiome-based investigations could reveal important mechanisms underlying waste bioconversion and improve the efficiency of BSF-based technologies.

Research on the environmental safety of BSF systems is also required. Future studies should assess the accumulation and transfer of heavy metals, pesticide residues, antibiotics, and microplastics through larval biomass and frass. Understanding these pathways is essential for ensuring the safe utilization of BSF-derived products in agriculture, aquaculture, and animal feed industries (Siddiqui *et al*., 2022) [17]. Another promising avenue involves evaluating the role of BSF in climate change mitigation. Comprehensive life-cycle assessment studies are needed to quantify greenhouse gas reduction, carbon sequestration potential, energy efficiency, and environmental footprints associated with BSF-based waste management systems under Indian conditions. Such studies could provide scientific evidence supporting the adoption of BSF technology within national climate action and sustainability programs (Parodi *et al*., 2021) [15]. The agricultural applications of BSF frass also deserve greater scientific attention. Future research should investigate its effects on soil microbial diversity, nutrient availability, plant growth, crop productivity, and long-term soil health. Comparative studies with conventional organic fertilizers and composts may help establish BSF frass as a sustainable agricultural input (Beesigamukama *et al*., 2020) [2].

Finally, large-scale implementation studies are required to evaluate the economic feasibility, social acceptance, and policy implications of BSF-based waste management systems in India. Pilot projects involving municipalities, educational institutions, vegetable markets, and rural communities could demonstrate the practical applicability of BSF technology and contribute to the development of sustainable "Waste-to-Wealth" models.

Overall, future interdisciplinary research integrating entomology, ecology, waste management, microbiology, agriculture, climate science, and environmental policy will be essential for fully realizing the potential of *Hermetia illucens*. Such investigations may establish BSF not only as a natural bio-recycling engineer but also as a valuable bioindicator species and a key component of sustainable environmental management in India and other developing nations.

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