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A Review of the Promising Effectiveness of Insects in Waste Management

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ABSTRACT

Waste management is an urgent global issue. Thus, developing innovative and long-term solutions is essential. Recently, there has been a growing interest in using insects for waste management as one of the main alternatives. One of the emerging applications is using insect larvae as a viable approach for breaking down hazardous organic waste and plastic waste. Aquatic insects effectively decompose water waste containing microplastics, as their decomposition rate has reached 50%. Another application uses vermicompost and insect-based bioconversion as bioeconomic waste management methods to produce pollution-free or non-toxic by-products from day-to-day waste. Insects such as black soldier flies, flesh flies, and some beetle species have been studied for their efficiency in converting various types of waste such as sewage sludge, municipal waste, food residues, restaurant and market waste, residual plant waste after oil extraction and non-organic waste into valuable resources. This article provides a comprehensive review of the promising effectiveness of insects in waste management, highlighting their ability to transform organic waste into valuable resources, minimize non-organic waste and contribute to sustainable practices.

KEYWORDS: Black soldiers fly larvae, Yellow Mealworm Beetle, Darkling Beetle, aquatic insects.

INTRODUCTION

In a world marked by swift population growth, we face two critical challenges: the imminent threat of food shortages (Kee, et al., 2023), which poses significant risks to both human health and the environment (Siddiqui et al., 2022), and the growth in waste volumes highlighting a fundamental reality. Waste remains an underappreciated asset until we harness it for productive purposes (Mannaa et al., 2024). The practice of utilizing insects in the conversion of overlooked waste into valuable resources is where innovation thrives. Insects are highly prolific and have broad adaptability to various food sources, making them a viable solution for the ongoing waste accumulation problem (Beesigamukama, et al., 2023) .

These exceptional creatures pave the way by efficiently converting various organic waste materials, including food remnants, animal byproducts, and agricultural residues (Shaboon et al., 2022). Interestingly, the idea of using fly larvae for organic waste processing was first proposed a century ago. (Čičková et al,. 2015) In modern agricultural biogas plants, utilizing biowastes in larvae breeding farms has become more common. This dual-purpose strategy helps us dispose of waste and yields biogas, a valuable byproduct. (Czekała et al., 2020) It is a harmonious synergy of waste reduction and resource generation. Their adaptability and efficiency in converting organic waste into valuable assets demonstrate their significance. (Mannaa et al., 2024) This review highlights the multifaceted role of insects while delving into the practices surrounding insect-mediated waste conversion, as they act not only as a remedy for waste management dilemmas but as champions of sustainability.

Aim of the Review

We aim to uncover innovative solutions for waste management that can mitigate environmental concerns by using insects. The current review focuses on four types of insects, as indicated in Table 1.

Table 1: The insects studied in the current review.

English name	Scientific name
Black Soldier Fly	*Hermentia illucens* (Linnaeus, 1758)
Yellow Mealworm Beetle	*Tenebrio molitor* (Fabricius 1778)
Darkling Beetle	*Zophobas morio* (Fabricius, 1776)
Flesh Fly	*Sarcophagidae sp. Sarcophaga* (Meigen, 1826)

The Role of Insects in Waste Management

Insects are widespread components of all terrestrial and freshwater food webs, although their collective biomass is minor compared to plants and microorganisms. As a result, it is frequently believed that these species contribute very little to ecosystem processes. Despite their small stature and total biomass, these creatures frequently modulate the quality and quantity of resources entering the food chain, with implications for ecosystem-level carbon and nutrient cycling. (Yang et al., 2014) Multiple processes, such as direct inputs of insect biomass, detrital biomass transformation, and indirect effects of predators on herbivores and detritivores, cause these effects. Typically, the impacts of these routes on the environment transpire. Insects aid in decomposing organic waste, which brings significant environmental benefits. One of the key advantages of vermicomposting is its ability to suppress pathogens and curial greenhouse emissions. Recent studies have shown that incorporating insect-based technologies for feed, oil, and organic fertilizer production can reduce carbon dioxide emissions by 55-83% and deplete conventional energy sources like fossil fuels by 46%, indicating higher environmental sustainability and a lower ecological footprint. (Van Phl et al., 2020).

Black Soldier Fly

Hermetic illucens are found in tropical and warm regions. (Üstüner et al., 2003) The black soldier fly's feeding is associated with the outdoors and livestock. It is found around decaying organic matter, such as rotting fruits and vegetables, animal manure, and human waste. These insects feed during the larval stage (Manyara, 2018). Once hatched, the larvae start to feed on the waste, thus achieving a dry mass volume waste reduction of ~55% (Myers et al., 2008; Newton et al., 1995; Sheppard,.1983). Their short life cycle (Figure 1) contributes to building a high-density population. The larvae have voracious appetites, and fresh material is processed extremely fast, reducing the production of bad smells to a minimum. An additional advantage of *Hermetia illucens* is its capacity to repel the oviposition of female house flies (Bradley and Sheppard,1984). It is a disease vector, especially in developing countries. Under ideal conditions (i.e. waste deposits), larvae can mature in two weeks. The food shortage and low temperatures can extend the larval period up to four months. (Furman et al., 1959).

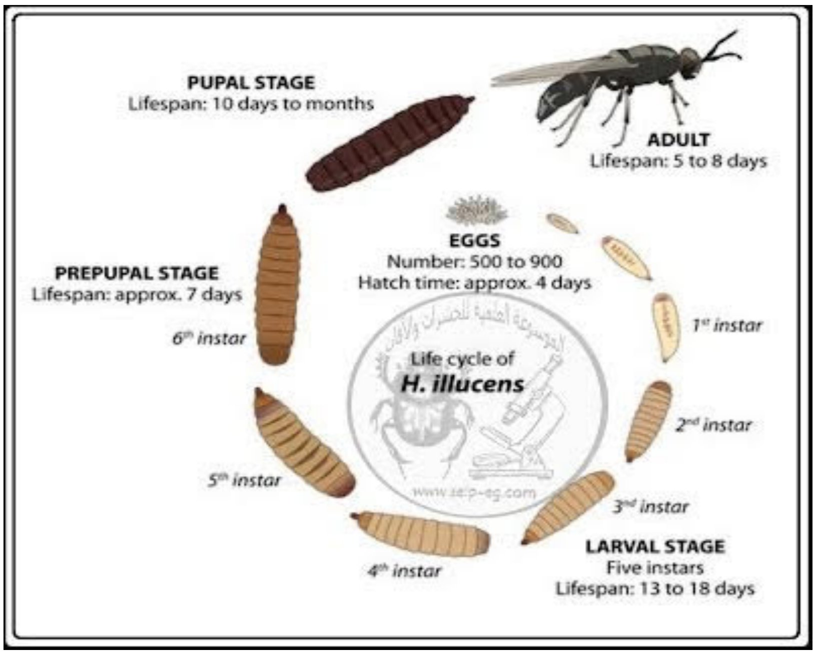

Figure 1: lifecycle of *Hermetia illucens* (De Smet et al.,2018)

The Role of Black Soldier Fly Larvae in Waste Management

Hermetia illucens has garnered increasing interest (Makkar et al., 2014; Smetana et al., 2016; Surendra et al., 2016), particularly since its initial use in the 1990s for waste treatment as an efficient method to convert bio-waste into protein- and fat-rich biomass for animal feed. The process involves feeding fly larvae with biowaste. *Hermetia illucens* can reduce the biomass of organic waste, such as slaughterhouse waste, food waste, fruit and vegetable waste, and human feces, by 50-60% (Ojha et al., 2020).

Hermetia illucens does not risk human health when compared to other fly species. *Hermetia illucens* adults have a short lifespan and do not feed due to redundant mouthparts. They typically avoid human habitats and foods and rely on stored energy from their larval stage in their fat body. The ample fat reserves in the larvae reduce or eliminate the need for adult feeding, minimizing the potential spread of diseases (Furman et al., 1959; Sheppard et al., 1983). *Hermetia illucens* can be utilized to manage organic waste and valorise various biodegradable wastes, which has led to extensive studies in this area. (Čičková et al.,2015 ; Mertenat et al., 2019 ; Czekała et al.,2020 ; Ojha et al.,2020 ; Siddiqui et al., 2022 ; Mannaa et al.,2024) Laboratory experiments at the Asian Institute of Technology (AIT) have been conducted to evaluate the digestibility of fecal sludge by Black soldier fly larvae insects. (Alamgir et al.,2011) The experiments used soldier fly larvae from a colony raised in a small 3m x 3m greenhouse equipped with an automated water spraying system. The larvae were subjected to various ratios of waste products (0%, 25%, 50%, 80%, and 100% fecal sludge) every three days until all the larvae had completed their transformation into prepupae. The experimental results revealed that in terms of fecal sludge processing, black soldier fly larvae (BSFL) not only survived and developed in pure fecal sludge but also significantly reduced the volume of sludge.

A recent study by Purkayastha and Sarkar (2023) demonstrated that BSFL can consume human feces, though the larvae had significantly lower body weight compared to those fed on food waste. Interestingly, the degradation and bioconversion of human feces were significantly enhanced when mixed with food waste, compared to larvae reared on human feces or food waste alone. These results suggest that optimizing rearing conditions particularly through various substrate mixtures, could enhance bioconversion and degradation even for challenging waste types like human feces, which have little food waste remnants and limited nutritional value after the absorption of nutrients in the human gut. Recognizing and extracting valuable products from human excreta is essential from a sustainability perspective. Another study tested the ability of BSFL to recycle biological waste (Abd Rahman et al., 2020). It was observed that BSFL has a remarkable ability (75%) to recycle biological waste, as 800 g of larval biomass was produced from 4 kg of waste. To improve the effectiveness of bioconversion. BSFL should be maintained under optimal environmental conditions, including humidity, nutrient composition, physical properties, temperature, and oxygen level.

Figures 2 and 3 present findings from a study exploring the metabolic, nutrient functions, and taxonomic composition of intestinal bacterial communities in BSFL fed on pig and chicken manure (Mannaa et al., 2024). The study revealed that Bacteroidetes, Firmicutes, and Proteobacteria were the dominant bacterial groups in the BSFL midgut in these systems. Bacterial genes such as cellulases, proteases, and lipases, which hydrolyze starch/cellulose, proteins, and lipids, respectively, play a role in producing enzymes within the BSFL midgut, aiding in the digestion and recycling of biomass waste and nutrients (Lee et al., 2014). A study also found that adding bacterial supplements, such as *Bacillus subtilis* to chicken manure, positively impacted BSFL cultures (Yu et al., 2011).

Supplements containing arthropods and Rhodococcus in the diet of BSFL are also promising. Faster-growing, harvestable larvae and pupae save industrial BSF production costs and increase benefits. A study on Black Soldier Fly (BSF) was conducted to evaluate greenhouse gas (GHG) emissions associated with biowaste processing and compare them to conventional composting methods. (Mertenat et al., 2019) The study used a life cycle approach to evaluate an Indonesian BSF processing facility's global warming potential (GWP). Previous research on the greenhouse gas emissions of BSF has often relied on data from other insects and compared BSF with other feed production or waste diversion in high-income countries. This study aims to fill this research gap by directly assessing GHG emissions from the BSF treatment process and comparing it to an Indonesian composting facility. The BSF treatment process involves using larvae to process kitchen waste into plastic bins. (Dortmans et al., 2017) Treatment took 13 days, with kitchen waste added regularly according to recommended procedures. Direct GHG emissions from the BSF processing process were assessed by conducting a gas sampling campaign at the facility (Chan et al., 2011). Gas samples were taken daily in triplicate to measure methane, nitrous oxide and carbon dioxide production. The results indicated that BSF larvae could effectively reduce biowaste with an average reduction of 50% and a biomass growth of 20-25% (wet weight). Methane production was estimated at 0.4 grams per ton of treated organic household waste, and nitrous oxide production was estimated at 8.6 grams per ton of treated waste. The study found that when considering direct greenhouse gas emissions, BSF processing had lower emissions than composting. In conclusion, this study indicates that BSFL biowaste treatment can lead to lower direct greenhouse gas emissions than traditional composting methods.

Production with low carbon

In regions with low- and middle-income economies, biowaste includes municipal solid waste from households' food, market, park, and food manufacturing plant residue, constituting a significant portion of waste, accounting for up to 70%. Typically, this bio-waste ends up in landfills and wastewater, contributing to approximately 90% of global waste sector emissions (Mertenat et al., 2019). Including greenhouse gasses like methane (CH4), ammonia (NH3), and nitrous oxide (N2O) during the decomposition process in landfills. To address this environmental challenge, redirecting biowaste to feed BSFL for mass production offers a sustainable alternative to landfills. It presents cost-effective raw materials for BSF protein meals and oils. This approach enhances the efficiency and sustainability of end-products. A case study in Indonesia highlights that BSF (Klammsteiner et al.,2020), indicated that waste treatment facilities produce fewer hazardous gas emissions (CO_2, CH_4, and N_2O) and consume less energy (electricity and diesel) when compared to open-windrowing composting. A heat map study also reveals a positive correlation between BSFL application and various environmental factors such as temperature, pH, C/N ratio, gaseous emissions and PB population. Moreover, insect-based protein meal, according to Smetana et al., (2016), is a significantly more environmentally friendly product with environmental benefits up to 2-5 times that of commercially available alternatives. This shift toward BSFL-based waste treatment offers a promising avenue for reducing greenhouse gas emissions and improving sustainability in waste management.

Black soldier fly larvae as an animal feed

Using BSFL to convert organic wastes into larvae or prepupae is an environmentally friendly and sustainable recycling technology (Diener et al., 2011). BSFL, with its variable nutritional content depending on the substrate and age, stands out as an excellent source of animal feed due to their high crude protein and crude fat content (Kim et al., 2019; Spranghers et al., 2017). BSFL can serve as animal feed in multiple forms, including processed options like dried larvae, extracted oil/protein meal, and live larvae. Protein extracted from BSFL larvae and pupae is a viable substitute for common feed ingredients such as soybean or meat meal (Čičková et al., 2015). Moreover, BSFL protein contains all ten essential amino acids required for animal nutrition: arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine (Halver et al., 1957, Halver and Shanks, 1960, Shumo et al., 2019). The quality of animal feed is influenced by the amino acid composition of the proteins (Muller et al.,2017). The amino acid content in BSFL can vary depending on the substrate the BSFL is fed with, and the highest total amino acid content was observed in BSFL fed with kitchen waste.

Table (2). Compares the waste reduction and bioconversion rates by BSFL on various substrates compared to chicken feed bioconversion (Siddiqui et al.,2022).

Substrate	Waste reduction (%)	Bioconversion rate (%)	References
Individual wastes			
Abattoir waste	46.3	15.2	Lalander et al. (2019)
Canteen waste	37.9	15.3	Gold et al. (2020a)
Cow manure	12.7	3.8	Gold et al. (2020a)
Digested sludge	13.2	0.2	Lalander et al. (2019)
Food waste-1	66.7	7.7	Salomone et al. (2017)
Food waste-2*	52.3	27.9	Ermolaev et al. (2019)
Food waste-3	55.3	13.9	Lalander et al. (2019)
Fruits and vegetable	46.7	4.1	Lalander et al. (2019)
Human feces-1	73.0	NA	Lalander et al. (2013)
Human feces-2	45.8	22.9	Banks et al. (2014)
Human feces-3	47.7	11.3	Lalander et al. (2019)
Human feces-4	43.9	20.7	Gold et al. (2020a)
Municipal organic waste	68.0	11.8	Diener et al. (2011a)
Poultry manure	60.0	7.1	Lalander et al. (2019)
Poultry slaughterhouse waste	30.7	13.4	Gold et al. (2020a)
Primary sludge	63.3	2.3	Lalander et al. (2019)
Swine manure	56.0	NA	Newton et al. (2005a)
Undigested sludge	49.2	2.2	Lalander et al. (2019)
Vegetable canteen waste	58.4	22.7	Gold et al. (2020a)

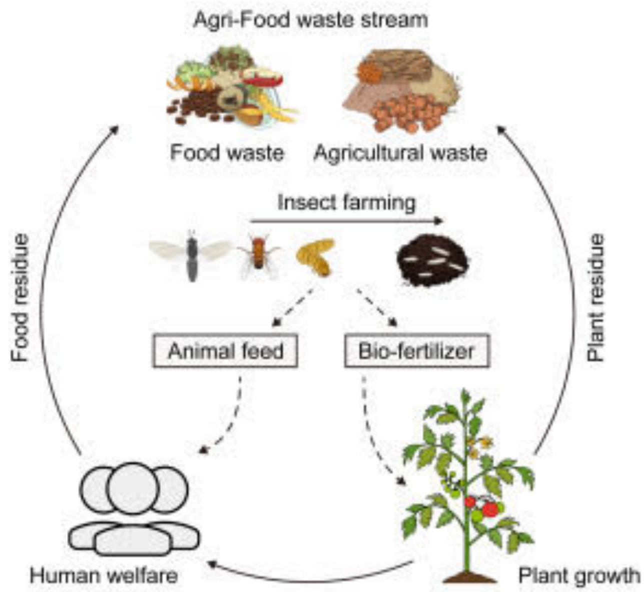

Figure 2: Black Soldier Fly Larvae Converting Waste to Value (Mannaa et al.,2024)

The Utilization of Insect Frass as Agricultural Fertilizer

Waste management challenges and soil degradation pose significant environmental issues that adversely impact global food security (Pimentel et al., 1975). Additionally, issues like micronutrient deficiency, low organic matter, and soil acidity hinder the effectiveness of mineral fertilizers (Kihara et al., 2016). Organic fertilizers serve as a cost-effective and viable solution for soil enhancement. However, their adoption needs to be improved due to extended production timelines, subpar quality, and insufficient on-farm organic material sources. Therefore, exploring alternative, cost-effective, and readily available sources of high-quality fertilizers is imperative. Numerous studies have investigated the use of insect frass, such as that from BSF and Yellow Mealworms (YMW), as potential sources of organic fertilizers that provide plants with essential nutrients and beneficial microorganisms. In this regard, BSF larvae swiftly convert organic waste into stable, mature, and nutrient-rich frass fertilizer in just five weeks, a process significantly faster than conventional composting, which can take 8-24 weeks (Beesigamukama et al.,2021). Crops such as maize, barley, cowpeas, French beans, tomatoes, and chilli peppers grown using BSF or YMW frass fertilizers have higher yields and nutritional quality than those cultivated with conventional fertilizers. Furthermore, applying BSF and YMW frass fertilizers as soil amendments has improved nutrient availability, nitrogen mineralization, and soil microbial activity, reducing the presence of soil-borne pathogens, soil salinity, and acidity. These factors collectively contribute to enhanced soil quality for crop production. To provide tailored recommendations for efficiently using insect frass in soil fertility enhancement and crop yield improvement.

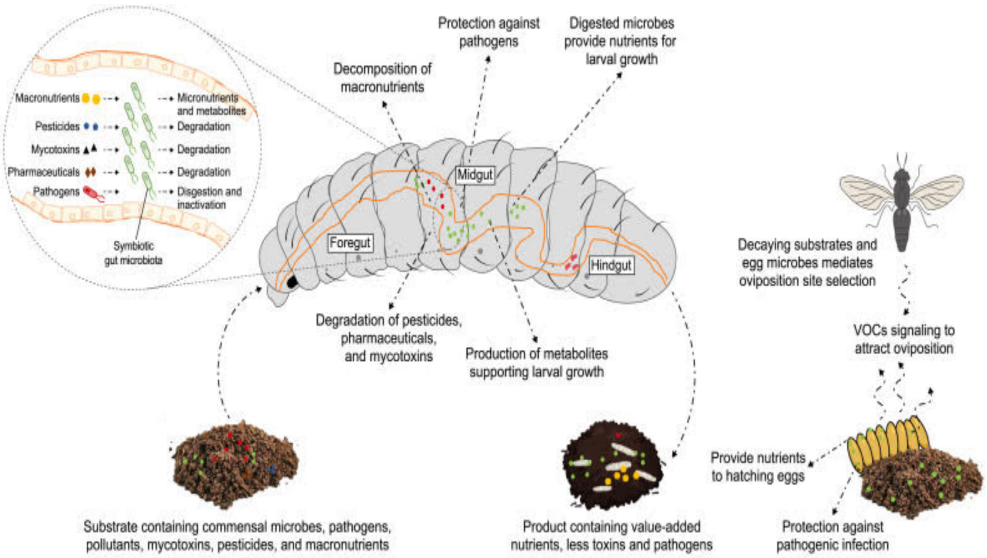

Figure 3: Illustration of the different roles of the gut-associated microbiota of the black soldier fly within the agri-food waste biorefinery system from the study conducted by (Mannaa et al., 2024)

Beetles and Their Ability in Plastic Waste Management

Beetles (Coleoptera) are a diversified and abundant species of insects that play a range of ecological functions in several sub-environments across most continents. (Marshall, 2018) Beetles in current habitats can be scavengers, saprophytes, carnivorous, herbivorous, or frugivorous. (Coleman et al., 2004) Tenebrionidae (darkling beetles) are a prevalent and diversified group of beetles spread out worldwide. It comprises soil-dwelling species in various habitats but is most closely connected with dry environments such as steppes and deserts. (Marshall, 2018) Darkling beetles undergo a complete life cycle encompassing four distinct life stages – egg, larva, pupa, and adult, each characterized by unique morphological features and behaviors. (Marshall, 2018) The larvae of certain Tenebrionidae species can be found in three primary soil textural categories: clay, loam, and sand. (Calkins & Kirk, 1975) In their natural habitats, *Zophobas morio* and *Tenebrio molitor* are considered generalist omnivores, consuming decaying plant material, fresh plant material, decaying insects, and fungi (Marshall, 2018), which makes them ideal candidates for decomposing organic waste**.** The developmental stages of *Zophobas morio* and *Tenebrio molitor* are highlighted in Figure 4.

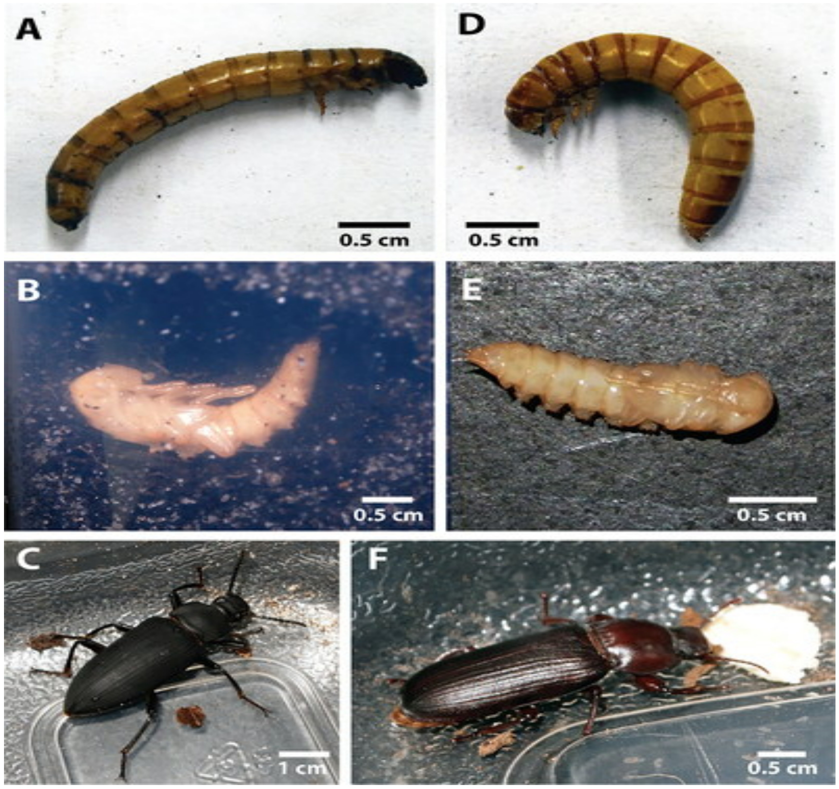

Figure 4: Developmental stages of the studied darkling beetle species. In the left column, *Zophobas morio* stages: (A) larva, (B) pupa, and (C) adult; in the right column, *Tenebrio molitor* stages: (D) larva, (E) pupa, and (F) adult (Hayden et al., 2021)

The Use of Insects in Plastic Waste Management

Traditional plastics such as polyethylene (PE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and other polymer compounds are known for their prolonged degradation in various environments. (Wang *et al*., 2022) However, more recent research revealed many microorganisms capable of breaking down polymers in natural environments, including soil, seawater, sludge, and compost. The intriguing relationship between insects and plastics traces its origins to consumer complaints about insects damaging chocolate-based consumable packaging. (Terence, 1997) Observations of insects destroying and consuming plastic packaging materials shed light on the degradation potential of these creatures, including insects belonging to the order Coleoptera. In recent years, studies have been conducted on the larvae of beetles, including *Tenebrio molitor* and *Zophobas morio*, and their ability to reduce plastic waste by feeding.

Studies Conducted on *Zophobas morio* in Plastic Waste Management

A recent scientific study revealed the remarkable resilience of superworms, as they demonstrated the ability to grow into beetles on a strict PBS foam diet. (Jung et al., 2023) This study acquired superworm larvae (*Z. atratus*) from a local supplier, Mealworm Nara, in Yeoju, Korea. These larvae had a length ranging from 5 to 6 cm. The life cycle of superworms consists of four stages: egg, larva, pupa, and adult, with a significant portion of their lifespan spent in the larval stage. These larger-than-average larvae exhibit improved mobility, heightened food consumption, and enhanced cutting capabilities. Collectively, these attributes enhance their effectiveness in breaking down plastic materials. Before commencing the feeding experiment, the superworms underwent 48 hours of fasting. A total of 30 superworms were housed in a polypropylene container (dimensions: 103 x 78.6 mm), and they were provided with PBS foam (4 g) as their sole diet. For comparison purposes, three control groups were established: the first group was given bran, a widely used feed in the industry; the second group received PS, a common plastic studied for superworm plastic degradation; and the third group was deliberately left unfed to induce a state of starvation. The superworms were kept for four weeks at a temperature of 26 ± 1°C. Deionized water was supplied to maintain adequate moisture levels, and any deceased superworms were promptly removed. The superworms' survival rate, changes in body weight, and plastic consumption were recorded every seven days, with all treatments conducted in triplicate. Every seven days, 4 g of PBS, 2 g of PS, and 2 g of bran were replenished. After the experiment, superworms exclusively fed with PBS exhibited a survival rate of 95.2 ± 1.6%, which was on par with that of bran-fed superworms (95.6 ± 4.4%) and exceeded the survival rates of PS-fed (90.7 ± 2.7%) and starved (84.4 ± 2.9%). The average weight of super worms that consumed bran, PBS, and PS increased by 32.4 ± 2.6% (equivalent to 32.23% in dry weight; 212 mg superworm−1), 5.1 ± 0.5% (equivalent to 4.77% in dry weight; 33 mg superworm^{-1}), and 3.6 ± 5.9% (equivalent to 3.30% in dry weight; 23 mg superworm^{-1}), respectively. In contrast, the average weight of unfed superworms decreased by 11.1 ± 2.1% (equivalent to 9.67% in dry weight; 67 mg superworm^{-1}).

These results indicated that PBS-fed super worms exhibited similar survival rates to bran-fed super worms and experienced a 5.1% increase in weight during the experiment, demonstrating that super worms can derive their energy and nutrition for growth from digesting PBS. Previous studies have reported similar trends, with comparable survival rates in PS-fed superworms (ranging from 90% to 100%).

Studies Conducted on *Tenebrio* Monitoring Plastic Waste Management

An experiment in 2023 was conducted studying *T. molitor* larvae's ability to degrade polyurethane used in refrigerator insulation by Zhu et al., (2023). The replacement of refrigerator insulation often leads to the disposal of significant quantities of waste refrigerator polyurethane (WRPU). While insect larvae such as mealworms have been employed in the biodegradation of pristine plastics, there is limited knowledge regarding their ability to degrade WRPU. This study conducts a comprehensive investigation into the degradation of WRPU by mealworms, examining micro-morphological changes, composition variations, and alterations in functional groups within the WRPU, as well as characterizing the properties of the resulting frass. The findings reveal that WRPU debris in the frass indicates that mealworms both ingest and degrade WRPU. The carbon content in WRPU-based frass was lower than in WRPU, suggesting that mealworms utilized WRPU as a carbon source. Furthermore, the study shows that urethane groups in WRPU were broken down, while certain C=C and C-H bonds in the isocyanate-derived benzene rings disappeared after mealworm ingestion. Thermal analysis indicated a lower weight loss temperature for WRPU-based frass compared to WRPU, signifying reduced thermal stability in the ingested material. Carbon balance analysis confirmed increased CO2 release from ingested WRPU, suggesting partial mineralization. Interestingly, the carbon content in the mealworm biomass that ingested WRPU decreased, possibly due to insufficient nutrient supply, impurities, and odor influencing the mealworms' appetite. Additionally, the study revealed that WRPU had a considerable impact on the gut microorganisms of mealworms. These collective findings provide strong evidence of mealworms' capacity to degrade WRPU. Yellow mealworm (*Tenebrio molitor* L.) larvae have also demonstrated their ability to break down and depolymerize polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC). In a study conducted in 2022 (Jin et al., 2023), mealworms were employed to facilitate the biodegradation of these plastic materials, which included PE, PS, and PVC. Furthermore, the research delved into the repercussions of plastic degradation on the growth and developmental aspects of yellow mealworm larvae by closely examining various physiological indicators and the nutritional constituents of the larvae following plastic degradation. The findings revealed that the degradation of plastics (specifically PS, PE, and PVC) was notably enhanced when a feeding amount of 0.50 g was utilized. It's noteworthy, however, that at this concentration, the degradation of PVC led to an increase in the mortality rate of yellow mealworms. In contrast, the degradation of a smaller quantity of PS (0.10 g) positively impacted the nutritional value, with higher levels of crude protein (45.7 ± 2.08%) and phosphorus (1.23 ± 0.04%), along with a lower larval mortality rate (7.90 ± 1.10%). This, in turn, had a limited effect on yellow mealworms' overall growth and development.

Comparison Between *Z. morio* and *T. molitor* Abilities in Plastic Waste Management

A comparative study was conducted by Wang et al., (2022) observing the distinct plastic ingestion preferences and efficiency variations between the superworm (*Zophobas morio*) and the yellow mealworm (*Tenebrio molitor*). The study highlighted the concurrent alterations in their gut microbiomes. The survival and plastic consumption abilities of superworms (*Zophobas morio*) and yellow mealworms (*Tenebrio molitor*) on exclusive plastic diets are compared in this study. While both species exhibited the capability to survive solely on plastic diets, a side-by-side assessment of their plastic degradation had not been previously conducted. In a 35-day experiment, superworms and yellow mealworms were fed polystyrene (PS) and polyurethane (PU) foam plastics as their sole diets, with bran as a control. Superworms displayed 100% survival rates on all diets, albeit a slight weight reduction was observed after 20 days of consuming exclusive plastic diets. In contrast, yellow mealworms had 84.67% and 62.67% survival rates when fed PS and PU diets, respectively, with both plastic diet groups showing increased weights. Cumulative plastic consumption by superworms amounted to 49.24 mg-PS per larva and 26.23 mg-PU per larva, which were 18 and 11 times that of yellow mealworms, respectively. When normalized to mg/g-larvae, superworms exhibited a higher PS consumption rate, while both species displayed similar PU consumption rates. Notably, changes in the chemical functional groups of plastics found in their frass indicated oxidation and biodegradation processes occurring within the guts of both species. These transformations were associated with alterations in the gut microbial communities, with distinct dominant microbiomes related to the specific plastic feedstocks and the species of larvae. Superworms fed on PS showed increased relative abundances of unclassified *Enterobacteriaceae, Klebsiella, Enterococcus, Dysgonomonas, and Sphingobacterium*, while Hafnia was strongly associated with PS diet in yellow mealworms. *Enterococcus* and *Mangrovibacter* dominated in superworm guts for PU diets, whereas unclassified Enterobacteriaceae and Hafnia were strongly associated with PU feeding in yellow mealworms. These findings underscore both species' different plastic ingestion preferences and efficiencies linked to distinct dominant microbiomes, although similar changes in plastic chemistry were observed.

Flesh Fly

The adult is between 9 and 13 mm in size. Typically, the thorax of this fly has three black stripes and is light grayish. (Watson and Dallwitz, 2003) Males have stronger front legs and are hairier than females, which helps them when they try to copulate. Male and female flesh flies have red abdomen ends, which resemble the "tails" of many other species. The front femora are frequently light gray and somewhat bigger than those on the other legs. A characteristic black stripe with golden or yellowish edges runs between the eyes of adults. (Watson and Dallwitz, 2003) Adult flies eat a variety of liquid materials without biting. Most larvae feed on feces, carrion, and wounds. Because they feed on the eggs, nymphs, or larvae of more dangerous insects, the larvae of certain species of meat flies are advantageous. Common hosts of flesh flies include grasshopper nymphs, blow fly larvae, and smaller house fly larvae. The lateral view of *Sarcophaga dux* adult is presented in Figure 5.

Figure 5: Lateral view of adult *Sarcophaga dux*, a flesh fly Photograph by Lazaro A. Diaz, University of Florida.

The Role of Flesh Fly in Waste Management

In many parts of the world, *S. dux* (Diptera: Sarcophagidae), sometimes referred to as a meat fly, is a species of medicinal significance. (Cherix et al., 2012) Even though many fly species are regarded as serious pests, they also aid in the biodegradation of organic waste and are crucial to the recycling of organic matter in the environment. (Čičková et al., 2015). According to Abo Hasan and Phun (2018), the flies' larvae included biologically active substances, including lectin, chitin, and antimicrobial peptides that will aid in the composting of organic waste and help decrease manures. This study first aimed to assess how different manures (chicken, goat, and cow) affected the development rate of the flies and their larvae's (*S. dux* and *M. domestica*) capacity to digest animal manures. Secondly, the effectiveness of manure reduction was compared in both species of flies. Third, the ideal growth of the two species of flies in three different types of manures was also determined. The flies frequently use animal manures, especially those from poultry and cattle operations, as part of their natural diets, because they are known to be voracious eaters, the larvae of common filth flies like *Sarcophaga dux* and *Musca domestica* can be employed to transform manures into a residue that is not contaminated. In a lab setting, one hundred freshly hatched *S. dux* and *M. domestica* larvae were each placed into 150 g of manures. After the larvae were deposited into the manures, measurements were made of the dry mass and mortality rate, and the initial wet mass and larval length were noted. Studies have shown that various types of manure significantly affect the growth of *M. domestica* and *S. dux* larvae ($p < 0.05$). Of the three manure types, cow manure produced the highest growth rate in M. domestica, while chicken manure led to significantly better development of *S. dux*, as indicated by the mean increase in wet mass and larvae length. *M. domestica* exhibited the highest mean dry mass in cow manure, while *S. dux* did so in chicken manure.

Figure 6: *Chironomus sp.* Larvae (image source: *Steve Hopkin).*

Figure 7: *Chironomus sp. adult* Contributed by *Nolie Schneider*

Figure 8: *Culex sp.* Larvae and adult By *CDC; Centers for Disease Control and Prevention,cdc.gov.Hydrophilus* sp.

Figure 9: *Hydrophilus sp***.** Adult by *Claudio Mendez*

Figure 10: *Aeshna sp.*Nymph, by *Christine Young.*

Figure 11: *Aeshna sp.* Adult by *Jim Petranka*

Aquatic Insects

Water wastage is seen as common because it is one of the most widespread wastes on the planet. The preservation of these ecosystems depends heavily on the aquatic species and insects that live there. With a decomposition rate of up to 50%, the Chironomus aquatic insect is one of the most efficient insects at breaking down aquatic waste, including microplastics. The eye spot, tube, abdominal plate, antenna, and abdominal tubes are the basic features that help identify Chironomus. Larvae and adults of *Chironomus* sp. are presented in Figures 6 and 7, and *Culex* sp. in Figures 8. *Hydrophilus* sp. adult is presented in Figure 9. Nymphs and adults of *Aeshna* sp. are displayed in Figures 10 and 11. *Culex pilosus* larvae have long antennae with a prominent tuft at the tips and a wide head. An oval gill is introduced at the base of the antennae on the ventral side of the larval head (Carpenter and LaCasse, 1955). Their siphon is upcurved, and at the end of the siphon is a curved preapical spine. *The Hydrophilus* beetles have a distinctively elongated and slender body. The largest beetle in this genus can reach a maximum size of 40 mm (Cranshaw, 2010).

The Role of Aquatic Insects in Water Waste Management

The low-lying desert region of EL Cola, which is roughly 14.6 km east of the city of Sohag (26° 33ˀ 04ꞁ N and 31° 50ˀ 55″ E), is home to the wastewater project where investigations on the use of aquatic insects for wastewater management were carried out. (Khedre et al.,2023) It is situated between a plateau made of limestone and a desert. This location is made up of several asymmetrical basins that span about 4.4 km2. A single basin, spanning approximately 1.27 km2, was selected for sampling due to its perceived closure. Specimens were collected from ten sampling stations around the basin to give a representative image of MP contamination. All samples were collected in January 2021; each point was around 100 meters apart. Aquatic insects were collected from 0 to 60 cm below the water's surface using a pond net with a 200 m mesh. Ten duplicates were taken at each sampling location at the same stations to collect silt and water. Every precaution was taken to avoid upsetting or releasing aquatic insects. Ten surface water duplicates (5 L) were collected using a steel bucket from each sample site after the first collection, sorting, and taxonomic identification in the field. These replicates were then stored in clean glass containers for laboratory analysis. Vials for collecting samples were promptly sealed to stop airborne contamination. According to the present findings, the insect under examination had fewer MPs after a 24-hour period, demonstrating its exceptional capacity for digestion. After twenty-four hours, the average number of MPs per insect in *Chironomus* sp. larvae dropped dramatically, with 53% of the MPs being expelled. The egestion of MPs of several freshwater invertebrates was examined, including diploids (*Sphaerium corneum*), frogs (*Gammarus pulex*), and flies. They proposed that the form of MPs may influence an organism's capacity to digest and egest MPs. It is, therefore, a helpful technique for looking at MP pollution in freshwater environments (Akindele et al., 2020). Numerous morphological, behavioral, and physiological traits are seen in aquatic insects (Phuge et al., 2020). Additionally, they are essential to the food chain because they filter organic particles, participate in the cycling of nutrients through leaf division, hunt insects and other fish, and provide food for other vertebrates and invertebrates. (Ribeiro-Brasil et al., 2021) Nevertheless, research on this insect and its application in the analysis of water waste is still lacking.

Aquatic insects' capacity to consume MPs

The quantity and kind of MP particles removed from the guts of several aquatic insects collected from the wastewater are displayed in Tables 3 and 12. With variations in the observed egestion ability, the results showed a decrease in MPs in all examined insect taxa following a 24-hour deputation period. Chironomus sp. and Culex sp. larvae showed a substantial decrease in the mean number of MPs per individual following the depuration stage ($p < 0.05$), with the egestion percentages of 53% and 40%, respectively. Aeshnidae nymphs had a 25% decrease in MP egestion ability, and adults of Hydrophilidae had the lowest percentage, only 9% of egestion. When the adult Hydrophilidae and *Aeschnidae nymphs* were permitted to expel their stomach contents spontaneously, the relative abundance of MPs was not substantially decreased ($p > 0.05$). When comparing gut contents evacuated samples to non-evacuated samples, the mean lengths of MP particles were shorter in all species studied; however, these changes were not statistically significant ($p > 0.05$) (Khedre, *et al.*, 2023).

Table 3 : Microplastics abundance in aquatic insect samples with non-evacuated and evacuated gut content (*Khedre et al.,2023*)

Microplastic abundance in aquatic insects' samples with non-evacuated and evacuated gut contents.

Order	Family/genus (stage)	FFG	Mean MPs particles/individual. Non-evacuated	Mean MPs particles/individual. Evacuated	Percentage of ejection	Mean length of MPs fibers (μm) Non-evacuated	Mean length of MPs fibers (μm) Evacuated
Diptera	Chironomidae/*Chironomus* sp. (larva)	CG (2)	0.88 ± 0.1	0.41 ± 0.15	53%	507 ± 182 (321–730)	482 ± 215 (343–620)
	Culicidae/*Culex* sp. (larva)	CF	0.25 ± 0.07	0.15 ± 0.02	40%	710 ± 108 (580–815)	695 ± 103 (580–810)
Coleoptera	Hydrophilidae/*Hydrophilus* sp. (adult)	CG (1)	2.12 ± 0.62	2.01 ± 0.50	9%	1258 ± 315 (980–1513)	1153 ± 394 (980–1326)
Odonata	Aeshnidae/ *Aeshnae* sp. (nymph)	p	4 ± 1	3 ± 1	25%	1190 ± 270 (986–1490)	1040 ± 109 (986–1092)

Substantial gut clearance was assumed after aquatic insects have been kept for 24 h in dist. water. (FFG legend: P = predators; CG = collector-gatherers; CF = collector-filterers). (Mean ± SD).

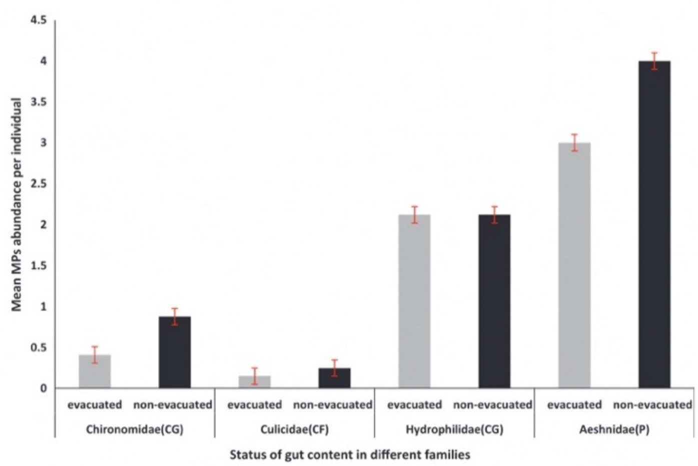

Figure 12 : Microplastics abundance in aquatic insect samples with non-evacuated and evacuated gut content. (Khedre *et al*., 2023)

Conclusion

This paper concluded that insects are ideal candidates for waste management. *Hermetia illucens* has gained interest in waste management due to its ability to convert bio-waste into protein-rich biomass. *Hermetia illucens* can reduce organic waste biomass by 50-60%. Research has shown that some insects, including beetle larvae such as *Tenebrio molitor* and *Zophobas morio*, can reduce plastic waste by feeding on it. The relationship between insects and plastics arose from observations of insects destroying and consuming plastic packaging materials. *Sarcophaga dux* has been used to biodegrade organic waste and plays an important role in material recycling, which will help reduce compost and convert organic waste into fertilizer. The aquatic *Chironomus sp* and *Culex* sp., *Hydrophilus sp. and Aeshna sp.* are known for their effectiveness in breaking down aquatic waste, including microplastics.

Recommendations

Based on this review, we hope to see the following implemented:

- Recognize the superiority of *Hermetia illucens* among insects with an ability to manage organic waste.
- Encourage increased future research and experimentation on the potential utilization of insects in waste management and recycling.
- Expand the scope of insect-based waste recycling by exploring a variety of insect species rather than restricting it to just one.
- Promote in-depth studies on aquatic insects and their pivotal role in managing freshwater waste, given its significance as a primary water source.
- Emphasize the application of insects to reduce organic waste and offal, replacing chemical methods for sustainability. Utilizing insects in research and experiments, rather than eliminating or disposing of them, will contribute to environmental preservation.
- Investigate the impact of insect-based waste management in landfill sites.
- Integrate insect-based waste management into broader recycling and waste management systems. This entails segregating organic waste and introducing suitable insect species to convert specific biodegradable materials, resulting in more efficient waste reduction and resource recovery.
- Enhance waste containment by employing sealed containers or boxes with secure lids to prevent house flies from accessing waste and breeding. It is crucial to ensure that containers remain tightly closed, especially in areas where waste is temporarily stored prior to disposal.
- Explore the potential for waste reduction through insect-derived products, which can be harnessed from organic waste materials.

Future Aspects

This article opens the door for government bodies such as the National Centre for Waste Management, the Ministry of Environment Water and Agriculture, the Ministry of Investment, and the Ministry of Energy to promising avenues for further research on utilizing insects in waste management. One key area of future exploration is incorporating insect farms in waste management practices as a cost-friendly alternative to traditional methods. Additionally, further research on insects and their role as decomposers can reduce the overall mass of landfill waste.

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