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Biodegradation of plastics by insects and their microbial symbionts: An entomological perspective

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Abstract
One of the most significant environmental concerns in the world, second only to climate change, is plastic garbage, which has lately been recognized as having an impact on all living forms, natural environments, and the economy. Given this difficulty, it is imperative to look for ecologically friendly alternatives, such as biodegradation, as an alternative to traditional disposal. But nothing is known about the processes and effectiveness of plastic biodegradation at the moment. The purpose of this study is to demonstrate the detrimental effects that plastic trash has on the ecosystem. Insects and gut microbes are also discussed, with a focus on their significant future contribution to the breakdown of plastics.

Keywords: Entomological biodegradation, plastic waste, sustainable entomology, plastic-eating insects, *plodia interpunctella*

Introduction

Since the 1950s, commercial plastic production has expanded at an astounding rate. Between 1950 and 2018, an estimated 6.3 billion tons of plastic were manufactured (Alabi *et al*., 2019) [1]. At the present growth rate, plastics output is projected to quadruple over the next 20 years (Lebreton and Andrady, 2019) [2]. Pollution from plastic garbage is now widely recognized as a serious environmental problem. Up to 6,300 million metric tons of plastic garbage have been created so far, according to recent research (Geyer *et al*., 2017) [3]. Nevertheless, less than half of the plastic garbage generated was recycled or dumped in landfills. Our planet is a "Plastic World", with a significant amount of the leftover plastic debris littering the oceans, continents, and every other part of the globe (Rochman *et al*., 2013) [4].

Hazardous chemicals will be discharged into the atmosphere as a result of the careless disposal of plastics on land and open-air burning, affecting all living things, natural environments, and public health hazards (Alabi *et al*., 2019) [1]. Given this difficulty, it is imperative to look for ecologically friendly alternatives for its breakdown, such as biodegradation as an alternative to traditional disposal (Ali *et al*., 2021) [5]. One crucial factor in lessening the consequences of plastic pollution is plastic biodegradation (Wierckx *et al*., 2018) [6]. The processes and effectiveness of plastic biodegradation, however, are not well understood at this time. Invertebrates, like insects, are discussed in the current review along with their function in the breakdown of plastics, with a focus on the potential importance of these organisms in the future.

Plastic's Current State

Over the past several decades, plastic production has seen a significant increase, reaching approximately 359 million tons by the year 2018 (Lebreton and Andrady, 2019). Due to this rapid expansion, plastics have become some of the most commonly used materials worldwide. Food, cosmetics, chemicals, medications, and detergents are all packaged in plastic. Polyethylene (PE) is the most widely used synthetic polymer, with an annual global output of around 140 million Mg (tonnes) (Sivan, 2011) [7]. Every year, 180 million Mg (tonnes) of plastic are produced, and both supply and demand are rising. As more people use plastic, the amount of plastic pollution in the globe is increasing. By 2050, it is anticipated that up to 26 billion tons of plastic garbage would be generated, of which over half will end up in landfills before entering ecospheres including wetlands and seas, causing significant environmental contamination (Maharaj Satwika *et al*., 2024) [8].

The Disposal of Plastic Waste and Its Impact

Plastic trash is becoming increasingly frequently acknowledged as the most significant environmental issue of our day, second only to climate change (Jambeck *et al*., 2015) [9]. Landfills containing plastic garbage occupy a large amount of space. Large volumes of chemicals are released when 10,000 tons of plastic garbage are disposed of in landfills, which occupy 0.067 hm2 of land (Lithner *et al*., 2011) [10]. These dangerous substances have the potential to seep into the soil and impact groundwater and soil quality. Lower agricultural yields can occur from PE trash buried in soil because it can alter drainage patterns, disrupt soil fauna, and degrade soil quality. The rate at which plastic pollution enters the ocean ranges from 0.48 to 1.27 million tons annually. In addition, the amount of plastic entering the ocean is doubling every ten years, which is an amazing rate (Crompton, 2007) [11].

Particles of plastic pollute the food chain and marine environment, especially foods meant for human consumption (Lusher *et al*., 2017) [12]. When plastic debris comprising PS, PE, PVC, and PET is burned, dioxins, nitro-PAHs, and other carcinogenic compounds, such as polycyclic aromatic hydrocarbons (PAHs), can be released into the air (Al-Salem *et al*., 2009) [13]. It is more probable that harmful pollutants that are eluted from plastic debris or in the form of tiny or microplastic particles would infiltrate food chains (Browne *et al*., 2008) [14] and have an impact on crucial ecological species including salt marsh grasses, mussels, and corals (Uhrin and Schellinger, 2011) [15]. Chemicals linked to plastics and tiny, microplastic debris may accumulate in the bodies of people and mussels, damaging bodily tissues and cells (Li JY *et al*., 2023) [16].

Plastics Degradation Techniques

Organically the slow rate of plastic decomposition leads to a buildup of plastic garbage, which is a major environmental hazard. Age, weathering, polymer type, temperature, pH, and radiation are some of the variables that impact plastic deterioration (Akbay and Özdemir, 2016) [17]. Due to a lack of suitable degrading techniques, plastic treatment comprises of 77% reclamation, 13% incineration, and 10% mechanical and chemical recovery. Because polyethylene waste is burned directly, vapours containing a range of harmful carcinogens, including ketones and acrolein, as well as greenhouse gases, like methane, are released into the air, polluting the soil and groundwater (Briassoulis, 2006) [18].

Despite the fact that mechanical recycling has been the primary method for recovering thermoplastic wastes, most recovered goods have had their qualities adversely impacted after several production cycles, which results in a low level of market attractiveness. Chemical recycling is an approach that can recover monomers and other materials from 61 various types of plastic trash, but how well it works depends on how much it costs and how well the catalytic agents work (Rahimi and García, 2017) [19]. Although plastic biodegradation by bacterial and fungal strains has been emphasized as a viable way to eliminate plastic waste without causing secondary pollution (Lee *et al*., 2020) [20], it has certain drawbacks, including slowness and the need for ideal conditions for biodegradation. A developing alternative is the biodegradation of plastic trash by arthropods; certain worms that consume plastic have been shown to be able to break down plastic and transform it into non-hazardous compounds (Bombelli *et al*., 2017) [21]. Extruded polystyrene, polyethylene, polystyrene, polyvinyl chloride, polypropylene, polyphenylene sulphide, and ethylene-vinyl acetate are the seven types of plastics that insects have been known to break down. Although research is ongoing, some theories suggest that insects gut bacteria and enzymes play a part in the way plastics break down in them.

Identifying Insects that Consume Plastics

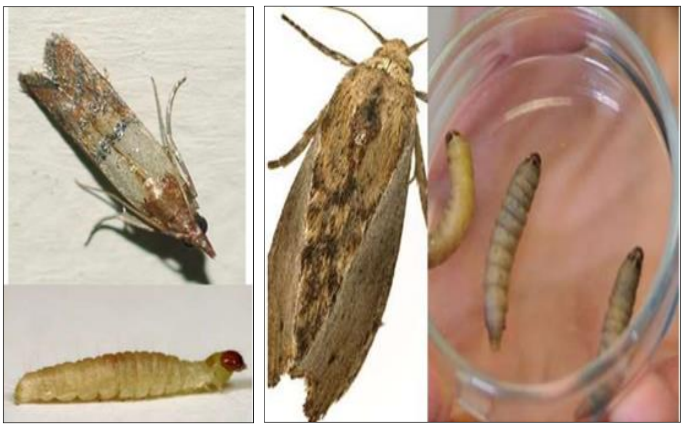
1. Lepidoptera

This order of insects contains moths and butterflies. Among the species in the Pyralidae family that are known for consuming plastic are the rice meal worm *(Corcyra cephalonica)*, bigger wax moth *(Galleria mellonella)*, lesser wax moth *(Achroia grisella)*, and Indian meal moth *(Plodia interpunctella).*

2. Waxworm

Due to their ability to ingest and digest beeswax, *G. mellonella* larvae may chew and swallow PE films, as illustrated in Figures 1A and 1B (Khyade, 2018 [22]; Yang *et al*., 2014) [23]. due to their structural similarities, G. mellonella's metabolic apparatus for beeswax metabolism could be used to PE metabolism. It is nowadays uncertain how gut microbiota and *G. mellonella* enzymes contribute to the breakdown of PE in both *in vitro* and in situ conditions. It is required for understanding how *G. mellonella* enzymes and bacteria contributes to the breakdown of PE (Kong *et al*., 2019) [24]. *G. mellonella* larvae's remarkable capacity to use pre-existing metabolic mechanisms to obtain energy from PE as their sole food supply (LeMoine *et al*., 2020) [25]. The worms softened thin-film PE shopping bags and transformed them into ethylene glycol (Bombelli *et al*., 2017) [21]. a study by Peydaei *et al*. (2020), salivary glands can facilitate the breakdown of polyethylene through the formation of pits and degradation intermediate with carbonyl groups. The function of suspected lipid oxidative enzymes is considerably greater in larvae that were fed PE, as shown by LeMoine *et al*. (2020) [25].

After being infected with 100 waxworms, a commercial PE shopping bag would lose 92 mg of weight in 12 hours (Weber *et al*., 2017) [27]. PE was also broken down by the microbial symbionts in the waxworm's intestines. The function of intestinal microbial symbionts in insect digestion has long been recognized; PE depolymerization has occurred in the case of waxworms (Yang *et al*., 2014 [23]; Engel and Moran, 2013) [28]. The guts of *G. mellonella* have been studied for PE biodegradation with Enterobacter sp. D1 (Ren *et al*., 2019) [29]. The gastrointestinal contents of *G. mellonella* were revealed to contain PEDX3, a PE-degrading fungus *Aspergillus flavus*. The two PE-degrading enzymes suggest that PE MPP remediation is a feasible replacement, and *A. flavus* strain PEDX3 could break down microplastic particles (Zhang *et al*., 2020). [30].



(A) **(B)**

Fig 1: A. Adult and larvae of Indian meal moth *(Plodia interpunctella)* B. Adult and larvae of Indian waxworm *(G. mellonella)*

3. Lesser Wax Worm

(A) (B)

Fig 2: A. Adult male *Achroia grisella* **B.** *Achroia grisella* caterpillar consuming silo-bag

A. grisella can consume silo bags, which are made up of three polyethylene layers and one anti-UV layer (Chalup *et al*., 2018) [31]. Lesser waxworms given PE, WC, or PE-WC finished their life cycle. The appearance of additional carbonyl and alcoholic groups in the frass and an increase in unsaturated hydrocarbon in PE samples fed less waxworms are indicated the synthesis of biodegraded intermediates (Kundungal *et al*., 2019) [32].

4. Meal Moths in India

By chewing and eating polyethylene (PE) packaging films, *P. interpunctella* larvae might harm them (Bowditch, 1997) [33]. The synthetic polymers are broken down by gut bacteria found in *P. interpunctella* (Mereghetti *et al*., 2017) [34]. In another investigation, *Bacillus sp.* YP1 and *Enterobacter asburiae* YT1 were recovered from the intestines of *P. interpunctella* larvae (Yang *et al*., 2014) [23]. They disrupted the PE film's surface and decreased its hydrophobicity after 28 days of incubation. The midgut larvae included strains of *E. tabaci* and *B. subtilis* subsp. *Spizizenii*, which are involved in degradation (Mahmoud *et al*., 2020) [35].

Table 1: Types of plastics broken down by insects and the microorganisms that live in them

Plastic Type	Insect Species	Associated Microorganisms	Reference
Polyethylene	*Plodia interpunctella*	*Bacillus* sp. YP1, *Enterobacter asburiae* YT1	Yang *et al*., 2014
	Galleria mellonella	*Enterobacter asburiae* YT1, *Bacillus* sp. YP1	Yang *et al*., 2014
	Achroia grisella	Not reported	Kundungal *et al*., 2019
	Corcyra cephalonica	Not reported	Kesti and Thimmappa, 2019
	Zophobas atratus	*Pseudomonas aeruginosa*	Lee *et al*., 2020
Polystyrene	*Tenebrio molitor*	*Exiguobacterium* sp. YT2	Yang *et al*., 2015b
	Zophobas atratus	*Pseudomonas aeruginosa*	Lee *et al*., 2020
Polyphenylene sulphide	*Zophobas atratus*	*Pseudomonas aeruginosa*	Lee *et al*., 2020
Ethylene-vinyl acetate	*Tenebrio confusum*	Not reported	Abdulhay, 2020
Polyvinyl chloride (PVC)	*Tenebrio molitor*	Not reported	Peng *et al*., 2020

5. Rice meal worm

Larvae of *C. cephalonica* are capable of breaking down low-density polyethylene. According to reports, any intestinal microorganisms might be the cause of LDPE degradation. The digestive tract of these larvae may manufacture the enzyme needed for the breakdown of LDPE (Kesti and Thimmappa, 2019) [36].

Coleoptera

This group of insects includes weevils and beetles. Some species of the Tenebrionidae family, including the meal worm *(Tenebrio molitor),* super worm *(Zophobas atratus),* and confused flour beetle *(Tribolium confusum),* have been discovered as plastic-feeding insects.

Mealworm

Fig 3: *T. molitor*

T. molitor has the ability to depolymerize and biodegrade polystyrene, polyethylene (Ghatge *et al*., 2020 [37]; Peng *et al*., 2020) [38], polypropylene (Yang *et al*., 2021) [39], and polyvinyl chloride (PVC). It was demonstrated that more kinds of mealworms from 12 different locations throughout the world has the ability to degrade PS, showing that mealworms often manage to do so (Yang *et al*., 2017) [40]. Mealworms are shown to be able to absorb rapidly and demolish up to 50% of ingested PS in under 24 hours, based on changes in chemical composition, molecular weight, and isotopic trace following tracks through the digestive system (Yang *et al*., 2015a) [41]. *Exiguobacterium sp*. YT2, a strain isolated from the gut of m *T. molitor*, has been found to be capable of breaking down 7.5% of the weight of PS in less than 60 days *in vitro* (Yang *et al*., 2015b) [42]. Brandon *et al*. (2018) studied how yellow mealworms degrade PE and plastic mixtures. Up to 49.0 ± 1.4% of the PE ingested converted to CO2 after being incubated with larvae. The molecular weights of the ingested polymer lowered by 40.1 ± 8.5% in mealworms fed PE.

According to studies adopting next-generation sequencing analysis, *Kosakonia sp.* and *Citrobacter sp.* are frequently found in the gut microbiome (Brandon *et al*., 2018) [43]. Polyethylene can be broken down via mealworms using enzymes including cellulose and esterase (Przemieniecki *et al*., 2020) [44]. *T. molitor* can biodegrade PP by gut microbe-dependent depolymerization with a range of microbiomes, according to Yang *et al*. (2021) [39]. *T. obscurus* ingested PS far quicker than *T. molitor*. TGA showed that *T. obscurus* larvae efficiently degraded PS according to the percentage of PS residue (Peng *et al*., 2019) [45].

6. Super worm

Polystyrene, polyethylene, and polyphenylene sulfide (PPS) foams are consumed by *Z. atratus* larvae (Li *et al*., 2020) [46]. *Pseudomonas aeruginosa* gut bacteria in *Z. atratus* have the ability to break down PS, PE, and PPS. The structure and characteristics of intermediate molecules produced during plastic biodegradation may have an impact on bacterial growth rates, and *P. aeruginosa* growth rates were not necessarily proportionate to biodegradation rates (Lee *et al*., 2020) [20].

7. Confused flour beetle

T. confusum may break down polyethylene foam, polystyrene, and ethylene-vinyl acetate. The larvae's mass weight increased over the trial, suggesting that plastic materials are ineffective as an energy source for larvae other than survival. According to Abdulhay (2020) [47], larvae fed PS, PE, and EVA lost 26.2, 31.4, and 45.8% of their weight, respectively. *P. davidis* larvae can consume PS, and after 14 days, they can survive only on Styrofoam by feeding each larva 34.27 ± 4.04 mg of PS foam. Fourier-transform infrared spectroscopy (FTIR) was used to confirm that the ingested Styrofoam had oxidized. On the PS film, which was separated from the stomach, *Serratia sp*. were grown (Woo *et al*., 2020) [48].

Conclusion

The development of innovative remediation techniques to eradicate plastic pollution may prove beneficial. The existence of possible bacteria has been suggested by recent methods on the breakdown of plastic by insect groups. In particular, the finding of symbiotic insect microbiota linked to plastic breakdown requires more investigation into the biodegradation of plastics. Insects' whole digestive systems contain gut microbes and digestive enzymes, which are crucial to their general physiological functioning. The worries about plastic pollution must be resolved, nevertheless, by thoroughly examining the molecular mechanisms behind the full physiological process of plastic decomposition in the insect's stomach.

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