Chapter

The Ability of Insects to Degrade Complex Synthetic Polymers

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Abstract

Insects while feeding, encounter a wide array of hydrocarbon polymers in their diet and the digestive tracts of various insects contain microbial symbionts that aid in the degradation of these polymers. Thus the idea of insects as synthetic polymer bio-degraders was established. Soon various insect, like mealworms, flour beetles, weevils, wax moths etc. particularly from the Coleopteran and Lepidopteran orders, were identified to have remarkable abilities to consume and degrade a wide range of synthetic polymers like polyethylene, polyurethane, polypropylene, polystyrene and polyvinyl chloride into lower molecular weight, simple, and nontoxic molecules which are eventually excreted as fecula. In this review we aim at congregating the diversity of polymer degrading insect fauna and understanding the underlying mechanism in which the insect's digestive enzymes works in synergy with the gut microbiota to digest complex synthetic polymers.

Keywords: synthetic polymers, insects, gut microbiota, enzymes, degradation

1. Introduction

The vast majority of eukaryotic biodiversity in terrestrial ecosystems is represented by insects [1]. While eating, insects come into contact with a wide range of hydrocarbon polymers, and the intestinal tracts of some insects contain microbial symbionts that aid in the decomposition of these polymers. Thus, the concept of the insect as a biodegrading organism for synthetic polymers was developed. Various insects of the Coleopteran and Lepidopteran orders have been observed to have remarkable abilities to consume and degrade a wide range of synthetic polymers such as polyethylene (PE), polyurethane (PU), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) into lower molecular weight, simpler, and nontoxic molecules that are eventually excreted as fecula.

Although microbial biodegradation appears sustainable, it has limits; and compared to plastic trash generation, its efficiency is modest. Furthermore, since biodegradation of a single polymer is usually a complicated process involving numerous enzymes, microbial consortia rather than a single species or strain biodegrade diverse natural and even synthesised polymers. As a result, a microbial assemblage will likely provide a more efficient biodegradation rate [2]. To overcome these limits, there was a need for a niche that would make plastic trash more accessible and bio-available to a dynamic microbial consortium. Recent research has shown that the digestive tracts of some invertebrates, notably insects, have microbial symbionts that help in the decomposition of various natural polymers that have similar structural arrangements to synthetic polymers [2, 3]. Therefore, the insect gut microbiome offered an efficient alternative for fast plastic degradation, and plastic degrading bacteria operating in concert with gut enzymes revealed increased breakdown inside the gut microbiome.

A better understanding of the function that the insect gut microbiome plays in the breakdown of plastic may be attained by actively force-feeding insects with different antibiotics and examining the variance in the molecular weight of the provided plastic feed between the insect culture with antibiotic suppressed gut microorganisms and the control insect culture without antibiotic treatment. This will allow for the acquisition of a better knowledge of the role that the insect gut microbiome plays in the degradation of plastic.

2. Insect's gut anatomy and the path to plastivory

Even though insects digest a wide range of foods, their digestive systems are largely the same. The adaptation of their diverse feeding guilds is primarily responsible for changes in their digestive tracts. The digestive tract of an insect can be structurally segmented into foregut, midgut, and hindgut. The foregut and hindgut can be divided into separate sections, each of which corresponds to a specific function. For instance, the foregut of insects is divided into pharynx and oesophagus and has a crop or diverticula for temporary food storage in addition to proventriculus for food grinding. The hindgut is separated into various regions, which include fermentation chambers and a separate rectum for retaining faeces before discharge. However, in many insects, the midgut serves as the main organ for digestion and absorption of ingested food materials [4]. Although it lacks an exoskeletal lining, the insect gut has a unique embryonic origin, having originated from endodermal cells. The peritrophic matrix serves as a protective lining for the epithelial cells lining the midgut of many insects. The peritrophic matrix divides the midgut into endo- and ectoperitrophic spaces, preventing microorganisms and abrasive food from coming into direct contact with the midgut epithelium thus preventing it from injury, pathogen infection etc. The peritrophic matrix also deactivates ingested toxins and pollutants such as pesticides and other inorganic or metal elements [5]. Furthermore, this matrix increases digestion efficiency by compartmentalising the digestion process and selectively transporting solutes and enzymes between the ectoperitrophic and endoperitrophic spaces. The peritrophic matrix further increases digestion efficiency by generating a countercurrent flow between the endo and ecto—peritrophic spaces, favouring nutrient absorption and minimising digestive enzyme loss by frass excretion [4, 6].

In this above described structure of the insect gut, resides a consortia of microorganisms which include protists, fungi, archaea, and bacteria. Fungi are common in the guts of insects that consume wood or detritus and are thought to aid digestion. Methanogenic archaea are most commonly associated with insects that feed on wood or detritus, like coleopteran beetles and isopteran termites [7, 8]. Apart from these, the most common organisms found in the almost all insect gut are a huge diversity of bacterial species. Insects that consume primarily wood as part of their diet (a behaviour known as "xylophagy") have gut microbial communities that are capable of taking part in the breakdown of cellulose [9].

Cellulose is a good source of carbon, but it appears in plant cell walls as crystalline or amorphous microfibrils, making it inaccessible to the host [10]. Here the bacteria participates to break down complex cellulose into simpler sugar residues and monosaccharides [11, 12].

The relative importance of microbial and host-derived enzymes varies as per insect species and feeding habits or diet composition. According to this theory, if insects are actively force-fed, they can degrade plastic and synthetic polymers. In general, mandibulate insects have the ability to masticate and consume plastic materials by breaking them down into smaller pieces. Even though plastic fragments are small, they have a greater surface area of contact with gut microorganisms and are therefore mixed with them. Gut microbes use the enzymes responsible for depolymerizing plastic polymers into oligomers, dimers, or monomers, and the depolymerized products are mineralised into CO_2, after which limited carbons are assimilated into biomass. Residual fragments and certain microorganisms in the gut are excreted as fecula, allowing for further degradation.

3. Synergy between insect gut microorganisms and synthetic polymers

Insect larvae owing to their capacity of consuming and absorbing synthetic polymers, especially plastic have recently opened a huge scope for researchers seeking the most efficient procedure of plastic biodegradation. Larvae of Coleopterans beetles are reported to consume and degrade plastics. *Tenebrio molitor* [13–18] and *Tenebrio obscurus* [15], the super-worm, *Zophobas asatratus* [14–16, 18], *Tribolium castaneum* [19, 20] and *Plesiophthalmus davidis* [21] etc. are few examples of members of the coleopteran order with this special ability. Besides coleopteran fauna, lepidopteran caterpillars, such as, Indian meal moth, *Plodia interpunctella* [3], the greater wax moth, *Galleria mellonella* [22–26], and the lesser wax moth, *Achroia grisella* [27] are also reported to digest synthetic polymers like polystyrene (PS), polyethylene (PE), polyvinyl chloride (PVC), and polypropylene (PP) (**Table 1**).

These insect larvae use their mandibles to consume plastics or diets that are high in plastic content. The gut symbiont and commensal microbiota of insect larvae undergo alterations when they are forcibly fed or co-fed plastic feed. In general, regardless of insect species or polymer type, consuming plastic alters the relative abundance or diversity of certain Operational Taxonomic Units (OTUs) likely Enterobacteriaceae, Enterococcaceae, and Streptococcaceae in comparison to larvae fed natural, plastic-free diets [15]. These OTUs subsequently follow a three-step process to degrade the ingested plastics: (a) microbial colonisation and biodeterioration, (b) enzymatic depolymerization (breakdown of polymer into simpler monomers) and (c) mineralisation.

The microorganisms initially colonise on the polymer either individually or in consortium (colonisation), which is assisted by various polysaccharides and/or proteins [45]. Following that, the interplaying polysaccharides and cysteine-rich proteins permeate the surface, changing the size of the polymeric pore [46]. These alterations cause biodeterioration. The durability and resilience of the polymer will decrease over time, but its surface area will expand, giving microbes a bigger surface area to adhere to. Various bacterial cells often produce an extracellular slime material that promotes adhesion and resulting in a slow positive feedback by increasing pollutant build-up, allowing for increased microbial proliferation [47]. Various bacterial cells often produce an extracellular slime material that promotes adhesion

Insect			**Consumable Plastics**	**Insect gut microbiota**	**Microbe types**	**Interplaying enzymes**	**Reference**
Common name	**Scientific name**	**Order & Family**					
Cigarette beetle	*Lasioderma serricorne*	Coleoptera; Ptinidae	Polyethylene (PE) Polypropylene (PP) Polyester	*Symbiotaphrina kochii*	Symbiotic yeast	Cutinase-like enzyme (CLEs)	Riudavets et al., [28]; Dowd and Shen [29]; Vega et al., [30].
Lesser grain borer	*Rhyzopertha dominica*	Coleoptera; Bostrichidae	Polyethylene (PE) Polypropylene (PP)	*Aeromonas liquifaciens*	Bacteria	Lipase Chitinase Protease	Riudavets et al., [28]; Anand and Pant [31].
Yellow Mealworm	*Tenebrio molitor*	Coleoptera; Tenebrionidae	Polystyrene (PS)	*Exiguobacterium sp* strain YT2	Bacteria	Alkaline proteases Alkali-tolerant esterase Hydrolase	Yang et al., [17]; Yang et al., [32]
			Polypropylene (PP)	*Kluyvera sp* *Citrobacter sp*	Bacteria		
			Polyethylene (PE)	*Kosakonia sp*	Bacteria		
Dark mealworm	*Tenebrio obscures*	Coleoptera; Tenebrionidae	Polystyrene (PS)	Spiroplasmataceae Enterococcaceae	Bacteria	Further research needed	Peng et al., [15]
Red flour beetle	*Tribolium castaneum*	Coleoptera; Tenebrionidae	Polystyrene (PS)	*Acinetobacter sp* AnTc-1	Bacteria		Wang et al., [19, 20]
Darkling beetle	*Plesiophthalmus davidis*	Coleoptera; Tenebrionidae	Polystyrene (PS)	*Serratia sp* strain WSW	Bacteria	Lipase Protease Chitinase	Woo et al., [21]
Lesser mealworm	*Alphitobius diaperinus*	Coleoptera; Tenebrionidae	Polystyrene (PS)	*Pseudomonas sp* *Kocuria sp* *Cronobacter sp*	Bacteria	Hydroquinone Peroxidase	Cucini et al., [33]
				Aspergillus sp *Penicillium sp* *Hyphodermella sp* *Trichoderma sp*	Fungi	Protease Cellulase Lipase	

Insect			**Consumable Plastics**	**Insect gut microbiota**	**Microbe types**	**Interplaying enzymes**	**Reference**
Common name	**Scientific name**	**Order & Family**					
Super worms	*Zophobas atratus*	Coleoptera; Tenebrionidae	Polystyrene (PS)	*Pseudomonas* sp strain DSM 50071 *Klebsiella pneumoniae* *Alcaligenes* sp. *Acinetobacter* sp.	Bacteria	Monooxygenase Lipase Cutinase Esterase Polyurethanase	Yang et al., [32]; Luo et al., [34]; Kim et al., [35]; Tang et al., [36]
			Polyethylene (PE)	*Citrobacter sp*			
			Polyurethane (PU)	*Mangrovibacter sp*			
Rice weevil	*Sitophilus oryzae*	Coleoptera; Curculionidae	Nylon Polyethylene(PE Polypropylene	*Bacillus subtilis* strain TLO3 *Staphylococcus sp*	Bacteria	Hydrolase Lipase	Prasad et al., [37]; Riudavets et al., [28]
Saw-toothed grain beetle	*Oryzaephilus surinamensis*	Coleoptera; Silvanidae	NylonPolyethylene	Isolation of Bacterial OTUs are yet to be done	Endosymbiotic bacteria	Further research needed	Elijah et al., [38]; Hirota et al., [39]
Greater wax moth	*Galleria mellonella*	Lepidoptera; Pyralidae	Polystyrene	*Massilia sp.* FS1903 *Acinetobacter sp* *Bacillus sp* *Serratia sp*	Bacteria	Manganese Peroxidase, Hydrogen peroxide Lac and Lignin Peroxidase (LiP) Lipase Protease Polyurethanase	Bombelli et al., [22]; Zhang et al., [40]; Jiang et al., [41]; Ren et al., [42]; Cassone et al., [23]; Lou et al., [26]
			Polyethylene	*Enterobacter* sp. D1	Bacteria		
				Aspergillus flavus	Fungi		
Indian meal moth	*Plodia interpunctella*	Lepidoptera; Pyralidae	Polyethylene	*Enterobacter asburiae* YT1 *Bacillus* sp. YP1	Bacteria	Esterase	Yang et al., [3]
Lesser waxworm	*Achroia grisella*	Lepidoptera; Pyralidae	Polyethylene	The role of the gut microbes if any on the degradation ability is yet to pondered upon.	NIL	NIL	Kundungal et al., [27]

Insect			**Consumable Plastics**	**Insect gut microbiota**	**Microbe types**	**Interplaying enzymes**	**Reference**
Common name	**Scientific name**	**Order & Family**					
Rice Moth	*Corcyra cephalonica*	Lepidoptera; Pyralidae	Polyethylene	*Staphylococcus saprophyticus*	Bacteria	Information is unavailable as of now	Kesti et al., [43]
Crickets	*Gryllus bimaculatus*	Orthoptera; Gryllidae	Polyester polyurethane (PUF)	*Aspergillus flavus* G10	Fungi	Hydrolytic enzymes	Khan et al., [44]

Table 1.
List of various insects and the synthetic polymers they degrade with the interplaying microbes and host enzyme.

and resulting in a slow positive feedback by increasing pollutant build up, allowing for increased microbial proliferation [47]. A number of different microbial enzymes have now initiated the enzymatic degradation process by depolymerizing and bio deteriorating the plastic polymers. Microbial enzymes (exo-enzymes) do bio-fragment synthetic polymeric structures into shorter chain oligomers, dimers, and monomers. The smaller molecules permeate and pass through the semi-permeable outer bacterial membrane (bio-assimilation) before taking up the depolymerization products (monomers) to obtain energy for cell metabolism and biomolecule production. The larvae can use the depolymerization products in the synthesis of different biomolecules.

Polymeric structures of plastics can be divided into C–C backbone and C–O backbone based on microbial breakdowns. PE, PP, PVC, and PS are examples of synthetic polymers with C–C polymeric backbones that can also be biodegraded. Microbial oxidation begins with the hydroxylation of C–C bonds and the formation of primary and secondary alcohols after the first breakdown of long-chain polymers to shorter and lower molecular weight carrying oligomers or monomers. This process is aided by the enzyme alkane hydroxylase, which does terminal and subterminal oxidation. Alcohol dehydrogenase further oxidises these alcohols, producing aldehydes and ketones. Aldehyde dehydrogenase then produces carboxylic acids, which increases the number of carbonyl-groups. The final carboxylate molecules, which are chemically identical to fatty acids, are incorporated into the oxidation pathway by microbes that provide bio-assistance for this process. In the case of PS, this generic degradation process shows only slight variation. The phenyl moieties are connected to the alternative backbone atoms of PS, which has a linear carbon backbone. Because of its unusual structure, PS biodegradation is more complicated; the organic product styrene formed after initial polymeric fragmentation is processed under the influence of numerous dioxygenase, isomerase, dehydrogenase, hydrolase, and aldolase enzymes. Easter bonds in the chemical structure of synthetic polymers with C–O backbones, such as PU and PET, increase their hydrolyzability. Polyurethane (PU) is made up of di- or poly-isocyanate and poly-ols that are linked together by carbamate (urethane) bonds [48]. Carbamate bonds connecting the crystalline stiff segments are vulnerable to attack by microorganisms. Microbial ureases, esterases, and proteases are among the enzymes that interact during PU depolymerization. During the process of PU depolymerization, ureases are responsible for breaking the urea linkage, proteases are responsible for hydrolyzing the amide and urethane linkages, and esterases are responsible for hydrolyzing the easter bonds [49] After depolymerization, the poly-ols are dehydrogenated and oxidised to produce acetyl-CoA, which is then integrated into the TCA cycle or further valorized. Terephthalic acid (TPA) and ethylene glycol (EG) are ester-bonded together to form the polymer polyethylene terephthalate (PET) [50]. The ester linkages are hydrolyzed to produce polar hydroxyl and carboxylic groups by various PET surface-modifying enzymes such as PET hydrolases after hydrolysis and depolymerization of monomeric constituents such as ethylene glycol (EG), terephthalic acid (TPA), monoethylene terephthalate (MHET), and bis-2-hydroxyethyl TPA (BHET) [51]. The enzyme MHETase is activated to further degrade the intermediate MHET and BHET into TPA and EG, which are then transported into the bacterial cell for further metabolism by dioxygenases and dehydrogenases. Finally, the final metabolites are converted into acetyl-CoA and succinyl-CoA, which enter biochemical cycles for mineralisation processes [52]. Fecula are expelled as residual and undigested particles.

4. A brief account of insects degrading synthetic polymer

4.1 Lepidoptera

The Lepidopteran insects capable of degrading synthetic polymers are discussed and detailed below. Following that, an overview of interplaying gut bacteria (**Figure 1**) that function in synergy with the host gastrointestinal enzyme is included.

4.1.1 The Indian meal-moth

Plodia interpunctella (Lepidoptera: Pyraloidea), an adult Indian mealmoth with black-tipped feet and a black to brown small-headed caterpillar, feeds on cereals, fruits, and other similar items. The waxworm caterpillars live as parasites in bee colonies and eat on pollen, cocoons, and beeswax in addition to grain mix [53]. In meal wax, at least two intestinal bacteria were found: gram-positive strain YP1, Bacillus sp., and gram-negative strain YT1, *Enterobacter asburiae* [3]. The YP1 and YT1 strains were found to have roughly 11% and 6% net loss of PE polymers, respectively [3]. During inoculation, bacteria grow on PE sheets and gain weight, resulting in the formation of a liquid suspension within about a month, and finally, the hydrophobicity and tensile strength of PE decline. PE samples become less resistant to microbial destruction as they grow less hydrophobic [54]. Both the YP1 and YT1 bacteria adhere to PE films almost immediately and form biofilms within three hours after being inoculated, indicating that they are ready for biodegradation [55, 56].

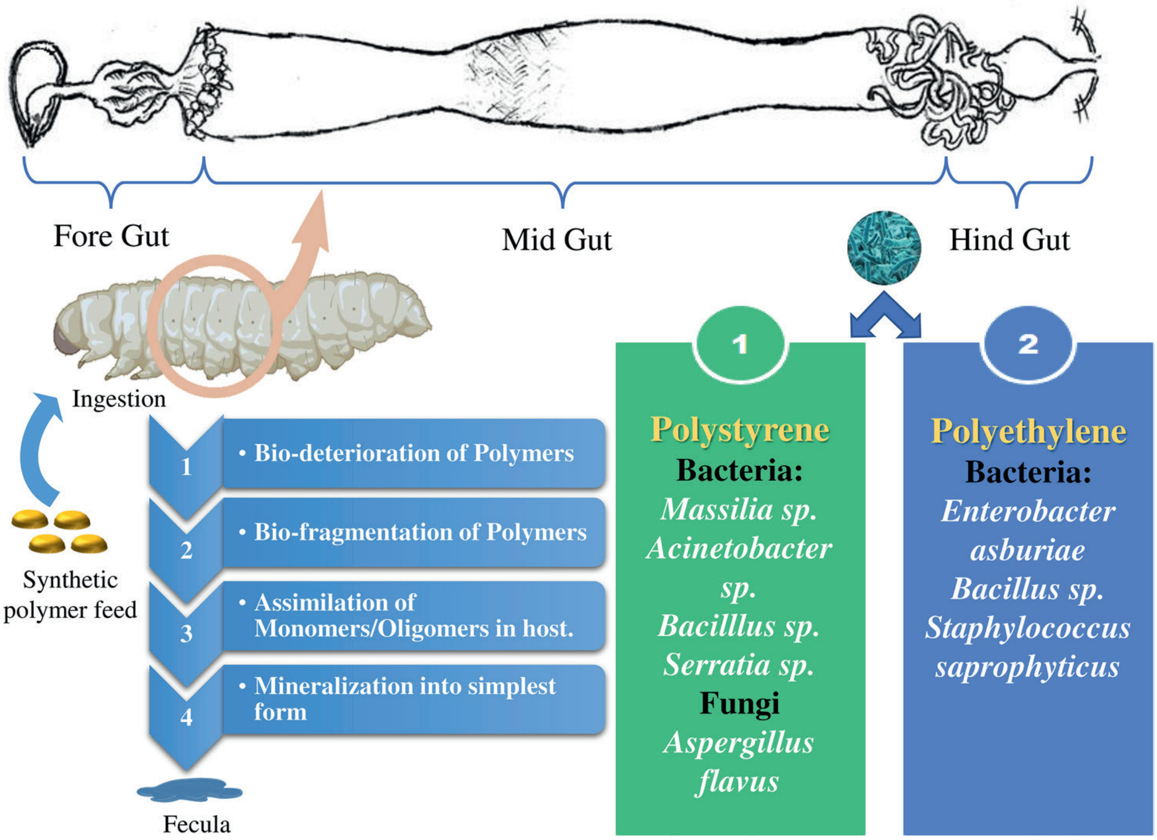

Figure 1.
Lepidopteran gut morphology and interplaying plastic degrading microbes.

A biofilm, as a non-soluble substrate, permits microorganisms to adhere to it efficiently. The presence of predominantly living bacterial strain cells on biofilm shows that PE metabolism provides these cells with the necessary nutrients [54–56]. The two bacterial strains also cause damage to the physical integrity of PE by changing surface topography, as multiple micro-pits and cavities are identified on the surface of biofilms using scanning electron microscopy (SEM) and atomic force microscopy (AFM) [3]. By increasing the quantity of carbonyl groups, the YP1 and YT1 strains elicit chemical alterations in PE [3]. The presence of the carbonyl group suggests that bacterial strains can oxidise PE materials to produce the carbonyl group, which is an important indicator of PE biodegradation. Furthermore, the weight loss of PE samples inoculated with two bacterial strains increases consistently, but the sample's molecular weight decreases. This process implies that the long-chain structure of PE is depolymerized, resulting in smaller molecular weight fragments. The chemical and physical alterations of injected PE samples show that wax worm gut bacterial strains YT1 and YP1 are capable of decomposing PE. Plastic-chewing insect larvae of the Indian meal moth, P. interpunctella, may thus represent a promising source of plastic-degrading insects.

4.1.2 The greater wax moth

The greater wax moth, *Galleria mellonella* (Lepidoptera: Pyraloidea), also known as the honeycomb moth, is a lepidopteran insect with brown-grey pigmented forewings and scaly hind wings are also reported for their plastic consuming ability. They are sexually dimorphous, 10–18 mm in length, and are distributed worldwide [57–59]. The larvae of the honeycomb moth are creamy-white, 3–30 mm in length [60], feed more intensely during earlier instars compared to later instars, and undergo eight to ten moulting stages [59]. Its larval stages are extremely damaging due to its voracious feeding habits, especially for bees and bee hives [59, 61]. The larva feeds on pollen, honey, wax, and broods and can tunnel through the comb [59, 62].

Honeycomb larva may devour PE films by generating pores and holes at a rate of more than two holes per hour per worm and can consume approximately 200 mg of PE mass in 24 h at a rate of 0.23 $mg/cm^2/h$ [53]. [22]. Ethylene glycol was identified as a metabolic by-product due to PE degradation through FTIR analysis [22] or by treating caterpillars with broad-spectrum antibiotics [23]. The intestinal microbiomes of these caterpillars were found to play a distinct role in the PE degradation process [23, 40, 42]. Additionally, the larvae fed on PE showed the highest microbial abundance in their intestines, demonstrating the intestinal microbiome's favourable response to the PE diet. As a result, the presence of microbe abundance in *G. mellonella's* gut implies that the insect is benefiting metabolically from PE substrate [23]. When microbes from the intestine of *G. mellonella* were cultured in a liquid C-free medium containing PE for 60 weeks, Acinetobacter species ACT126, as well as Enterobacter sp. [42], and the fungus Aspergillus flavus [40], were discovered to be excellent candidates for contributing to the biodegradation process. Moreover, by performing Atomic Force Microscopy (AFM), an apparent change in the topography of the PE surface was observed after treating the PE with the greater wax moth. Following further microbe contact to PE films, the PE surface roughens, facilitating microbe adherence to plastic films [22].

According to the data, *G. mellonella* works naturally with flawless metabolic machinery to biodegrade lengthy hydrocarbon chains [23]. The greater wax moth feeds on beeswax in the natural, which is constituted of a highly diverse variety of lipid compounds, including alkanes, alkenes, fatty acids, and esters, with ethylene being the most common hydrocarbon bond in PE. Although more research into the molecular intricacies of wax biodegradation is needed, it appears that one of the targets of digestion is the C—C single bond of aliphatic molecules. The presence of holes in PE films exposed to waxworms and the FTIR analysis of damaged PE revealed chemical disintegration of PE, including the breakage of C—C bonds [22].

Along with PE degradation, the greater wax moth, *G. mellonella* larvae, was also reported to chew and ingest PS after analysis of their frass through GPC, FTIR, and GC-MS analysis [26]. When PS was allowed to feed on *G. mellonella* as a sole diet, the larvae could reduce PS's weight by nearly one gm in three weeks. However, co-dieting with their conventional nutritional food along with PS has resulted in increased PS degradation. The gram-positive lactic acid-producing bacteria, *Enterococcus* sp., facultatively anaerobic gram-positive bacteria, *Bacillus cereus*, and the gram-negative rod-shaped bacteria, *Serratia marcescens*, were isolated from the *G. mellonella* larval gut and were suspected of participating in PS degradation [26].

4.1.3 The lesser wax worm

An adult lesser wax worm, *Achroia grisella* (Lepidoptera: Pyraloidea), is light brown with golden highlights and black scales with long filiform antennae. Generally, it is 8–13 mm long; females are larger than males [63]. Lesser wax moths are widely distributed in tropical, subtropical, and temperate regions. The caterpillars of *A. grisella* are considered serious pests of beehives as their larvae consume bee wax [64, 65].

Like other pyraloid moths, *A. grisella* has also been reported as a PE-degrading bio-agent. They can degrade PE but less rapidly than the greater wax worm and can complete their lifecycle by consuming PE films [27]. When PE films are left in direct contact with *A. grisella* worms, the lesser wax worms, after chewing the films, make holes in them within a few days, approximately 2 ± 1 holes per worm per hour, and one individual larva can degrade nearly 2 mg of PE film daily [27].

Though the PE diet is not a good source of nutrients to grow and survive, the larvae of *A. grisella*, by consuming PE as a sole diet, live for almost one month and may develop into a second generation [27]. However, when additional nutrients were provided for them, PE degradation increased rapidly, and as a result, the survival and reproduction rate of *A. grisella* increased. In the wild, *A. grisella* larvae consume and digest beeswax, which has strong chemical bonds similar to PE. The ability of *A. grisella* larvae to digest PE plastic might be due to the presence of PE-degrading bacteria within their gut or any other unique extracellular enzymes that have not been discovered yet. The *A. grisella* caterpillar treated PE films showed an increased deviation of PE mass and decreased residual PE, suggesting most larvae consume PE either by disintegrating or assimilating the PE.

FTIR and NMR analyses of frass confirmed that the biodegradation process successfully occurs in *A. grisella* larvae [27, 66]. The presence of new carbonyl and alcoholic groups with the increase in unsaturated hydrocarbons provides evidence for the biodegradation process of PE in the lesser wax worm. However, further research must understand whether this PE biodegradation is gut-dependent or independent.

4.2 Coleoptera

Representatives of Coleoptera, capable of degrading synthetic polymers are discussed and detailed below. An overview of interplaying microbes residing in the coleopteran gut (**Figure 2**) that function in synergy with the host gastrointestinal enzyme to degrade PE, PS, and PP is included.

4.2.1 The yellow mealworm

Adult yellow-meal-worm beetles, *Tenebrio molitor* (Coleoptera: Tenebrionidae), also known as darkling beetles, are black to brown, have moniliform antennae, and complete their life cycle holo-metabolically. The larvae of yellow mealworms typically measure about 2.5 cm or more in length and have lighter body colours than adults, with long and slender structures. Generally, the mealworm feeds on stored grains, vegetation, and dead insects [67].

The larvae of mealworm beetles are capable of chewing and eating PS (Styrofoam) plastic as their sole diet [17]. Other investigations further supported this fact [13, 15, 68]. The larvae were found to degrade almost half of the consumed PS within 12–15 hours in their guts [13]. PS samples inoculated with the *Exiguobacterium* sp. bacterial strain (YT2) were found to lose more than 7% of their weight after two months of incubation [69]. The bacterial strain (YT2) was noticed to cause surface topography changes on PS materials, and as a result, the hydrophobicity of PS decreases, and carbonyl groups form. As a result, PS weight loss is due to molecular weight loss [69, 70]. It has also been opined that besides *Exiguobacterium* sp., a variety of microorganisms play an essential role in the digestion process of mealworms [71, 72].

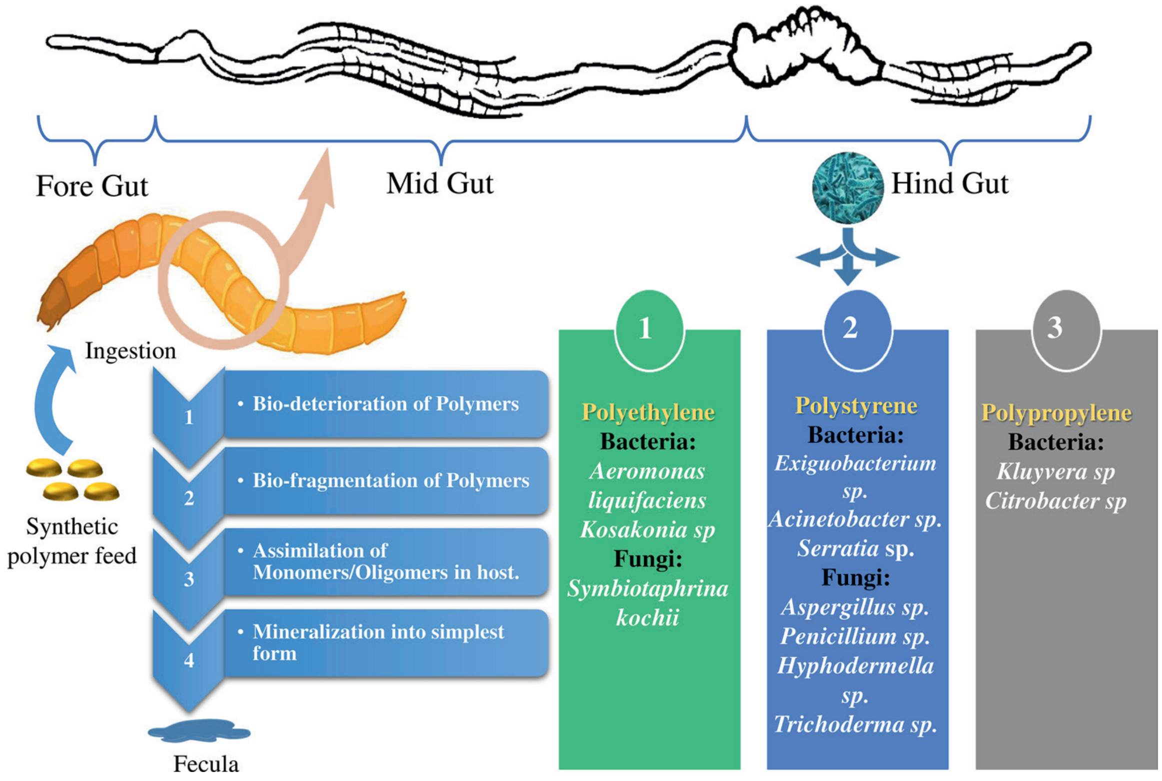

Figure 2.
Coleopteran gut morphology and interplaying plastic degrading microbes.

The information indicates that PS biodegradation and mineralisation occur within the gut of yellow mealworms [73]. During consumption, the larva generally produce hollows in Styrofoam samples, resulting in a decrease in Styrofoam mass [17] and the resultant small fragments of Styrofoam samples have an increased surface area. As a result, they were subjected to enhanced enzymatic depolymerization [17]. Another strain of mealworm (strain CA) was reported to be capable of biodegrading seven PS wastes [68]. Further investigation using mealworms from 12 different sources showed that mealworms from different regions could eat and digest PS, and those findings support the hypothesis that the capability of biodegradation of Styrofoam by mealworms is independent of their geographic origin and seems to be ubiquitous to the members of this species [68]. From this result, it could be assumed that chewing and consuming PS by yellow meal worms is their adaptive intrinsic behaviour, as they feed upon decaying forest vegetation in the wild [74]. Styrofoam-feeding mealworms had a significant survival rate, implying that Styrofoam feeding did not cause a negative effect on their survival ability [75, 76], but it was obvious that the PS degradation rate could notably be enhanced if the diet was supplemented with conventional sources of nutrition. Mealworms fed on such a diet could reproduce and enter into the second generation, which seemed to have a higher affinity for PS materials [68, 75, 76]. The temperature was also found to have corresponded with the PS degradation rate. It was found that at 250 C, the mealworm degrades PS at a significantly higher rate [68]. Moreover, PS consumption is influenced by the density of the foam materials, which is related to product hardness rather than molecular weight and thus likely to be chewed and consumed by mealworms. FTIR and NMR analysis revealed that due to cleavages at long-chains of PS molecules, they turn into low molecular weight phenyl derivative metabolites in the gut of mealworms [17, 36].

Yellow mealworms fed with PE and PS plastic each as the sole diet were found to cause mass loss of both the plastics. The yellow mealworms can degrade both PE and PS, but the degradation efficiency of PE was noticed to be much higher (48%) than PS (32%) on solo plastic diets. However, in both cases, degradation efficiency can be increased by up to 61% (for PE) and 54% (for PS) if the larvae are fed conventional food in addition to plastics [13]. The difference in mass loss of PE and PS might be due to the differences in density of the plastics, and it is presumed that less dense plastic molecules are ingested at a higher rate [68]. Among the present plastics, PE possessed a higher density than PS, which indicated that there might be other factors responsible for affecting the relative consumption rates of PE-PS plastic combinations. However, no clear evidence has yet been established to get an answer. Analysis involving HT-GPC, FTIR, and NMR studies certified that plastics could be degraded entirely and mineralised in the gut of the mealworms within a month approximately.

It was hypothesised that microbial communities significantly differed from the diets of the caterpillars or larvae. However, most microbial community members do not vary significantly in PE-fed diets among insects, but the composition is distinct in the PS-fed community. For example, *Citrobacter* sp. and *Kosakonia* sp., belonging to the family Enterobacteriaceae, were intensely associated with both plastic diets, viz., PE and PS [42] Both can use oxygen, which proves their participation in plastic degradation, as the biodegradation of both PE and PS is accelerated upon incorporating O_2 [32]. On the other hand, another two microbes, anaerobic gram-negative *Sebaldellatermitidis*, and gram-positive *Brevibacterium* sp., were uniquely associated with PE degradation [77]. Seven other microbes, viz., Listeria sp., Nitrospiradefluvii, Pedomicrobium sp., Aquihabitanssp., unclassified Xanthomonadaceae, Saprospiraceae, and Burkholeriales, were found to be associated with PS degradation in mealworm gut, further suggesting the significance of the microbial community in the plastic degradation process [78]. The information regarding the presence of various microbes in the mealworm gut suggests that mixed plastics of PS and PE could be depolymerized within the gut of the same mealworm. Therefore, the mealworm gut is not plastic-specific rather than independent in the degradation of any PE or PS plastics.

4.2.2 The dark mealworm

Adult dark meal-worm, *Tenebrio obscures* (Coleoptera: Tenebrionidae), also known as mini mealworms similar to yellow mealworms in appearance, are also known for their plastic-consuming ability. The larvae of dark meal worms are 1.5–2.5 cm in length, possess dark black rings on their abdomen, and become dark with maturity. The larvae have higher light sensitivity than yellow mealworms [15]. They usually consume seeds, vegetables, flour, and oats [68].

The larvae of dark mealworms were found to have the ability to degrade PS [15, 32], the depolymerization rate being higher than equally sized yellow mealworm larvae [15]. When dark meal worms were supplied with PS as their sole diet, mass loss of PS was found to be 55% in a month, but the amount of PS degradation was increased by 67% when the larvae were co-fed with supplementary food [15]. The investigation suggests that PS degradation ability can be achieved at a higher tempo when the insects are allowed to feed on a nutrition-rich co-diet. GPC and FTIR analysis supported that PS degradation was found to be operated by the active participation of gut bacteria residing in the dark mealworms. Before feeding PS, the gut microbiome was found to have higher diversity in *T. obscurus* than in *T. molitor* [15]. According to microbial community analysis, bacteria from the Enterococcaceae, Spiroplasmataceae, and Enterobacteriaceae families were particularly associated in their guts for PS depolymerization and degradation [15].

4.2.3 The super worm

Super worms, *Zophobas atratus* (Coleoptera: Tenebrionidae), also known as blind click-beetles, have very dark elytra on their cover, and after attaining maturity, the beetles become darker and are then called “black beetles.” Superworms have mandibulate mouthparts like mealworms, which provide these species the ability to chew and eat plastic.

Super worms are also found to chew and eat Styrofoam as their sole diet [79], and when they were left on Styrofoam samples, they instantly started to ingest and penetrate through the blocks and made hollows in the blocks within an hour [68]. *Z. atratus* can consume up to 0.58 mg of Styrofoam per day, which is four times more than mealworms (0.12 mg/day/worm) [17, 32]. Interestingly, the survival rate of super worms eating Styrofoam was almost equal to that of a regular diet, which indicates that super worms can complete their lifecycle by consuming Styrofoam diets [32]. After passing through their guts, the consumed long-chain PS molecules were degraded into low molecular weight products, styrenes, which were again mineralised into CO_2 [32]. Moreover, an antibiotic suppression assay using a combination of gentamycin, rifampicin, and streptomycin indicated that repression of gut microbiota by antibiotics diminished the ability of superworms to degrade PS and, therefore, confirms that the gut microbiota plays an important role in PS degradation in superworms [32, 35, 36]. Three bacterial strains, *Aeromonas* sp. and *Klebsiella pneumonia* from Enterobacteriaceae [36] and *Pseudomonas* sp. [35] from Pseudomonadaceae have been isolated from *Z. atratus* gut and confirmed their ability to degrade PS.

4.3 Orthoptera

4.3.1 Crickets

Orthopteroid fauna like crickets, such as *Gryllus bimaculatus* are also found to consume polyurethane (PU) plastics [44]. It has been noticed that *G. bimaculatus* is capable of consuming a diet that is 63% more rich in polyurethane (PU) than its usual food. Nine distinct microbial organisms, including bacteria and fungus, were identified in their digestive tracts which might take part in PU digestion. The fungus strain *Aspergillus flavus* G10 was isolated and identified from their gut after PU-degrading activity assays. The fungus was also noted to be responsible for PU degradation [44]. However, more research needs to be done on effective insect species as well as the potent gut microbial organism that are capable to degrade PU.

4.4 Other insects

There are some other insects from coleopteran and lepidopteran order that is seen to degrade synthetic or natural polymers (**Table 1**). Insects like cigarette beetles (*Lasioderma serricorne*), lesser grain borer (*Rhyzopertha dominica*), rice weevil (*Sitophilus oryzae*), saw toothed grain beetle (*Oryzaephilus surinamensis*)—from order coleoptera are among those, that have potential in digesting polyethylene or structurally similar polymers. Other Coleopterans namely red flour beetle (*Tribolium castaneum*), darkling beetles (*Plesiopthalmus davidis*) and lesser mealworm (*Alphitobius diaperinus*) are capable of degrading polystyrene or alike polymers. Other Lepidopterans like Rice moth (*Corcyra cephalonica*) and Isopteran Termites owing to their feeding habits of complex natural polymer have immense possibilities in degrading synthetic polymers.

5. Conclusion

In recent years, there has been a significant increase in the production of plastic due to the proliferation of its usage in areas ranging from the domestic sphere to multiple business spheres. However, improper treatment and management of plastic waste disposal have led to the accumulation of this material in the environment, which poses threats to the health of living species as well as to the health of humans. The most common petroleum-based polymers, PE, PP, PS, and PVC, have been thought to be non-biodegradable for many years. However, recent studies have shown that these polymers can be degraded by the microbial communities either on their own or with the active participation of the microbial activities that are present in the larval guts of certain insects. The knowledge that is currently available about the role that insects play in the breakdown of plastic is quite restricted, and as a result, several questions on the process of plastic degradation via insects are still unclear. It has not yet been determined what the precise processes underlying the degradation process are or what the function of the enzymes should be in this process. However, the good news is that the capability of some insects to degrade compounds that are rarely biodegradable or even non-biodegradable may be employed for the practical applications for the waste management programme, which can be shown to be extremely helpful for the health of the environment.

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